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AN EXPERIMENTAL INVESTIGATION INTO THE ACTION OF DIFFERENTIAL PRESSURE ON CERTAIN MINERALS AND ROCKS, EMPLOYING THE PROCESS SUGGESTED BY PROFESSOR KICK

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SUMMARY

INTRODUCTION

In a paper which appeared some years ago the results of an experimental investigation into the flow of marble were presented.[1] As this line of investigation seemed to be one which promised to yield additional results of interest if further developed, a grant was made to the present writer by the Carnegie Institution of Washington for the continuance of this work. A more complete equipment for

[1] F. D. Adams and J. T. Nicolson, "An Experimental Investigation into the Flow of Marble," *Phil. Trans. Royal Soc. of London* (1901), Ser. A, CXCV, 363–401.

experimental study was thus secured, the phenomenon of the flow of marble was further studied, and the investigation was extended to other rocks and to various rock-making minerals.

In the present paper it is proposed to describe briefly the results obtained in a single line of the investigation—that in which a method suggested many years ago by Professor Kick was followed. This method, however, while giving certain interesting results, especially with the softer and more plastic rocks, has proved to be less suitable for the development of high differential pressure and for otherwise reproducing the conditions which obtain in the deeper parts of the earth's crust, than the method suggested by the present writer and employed in the research into the flow of marble to which reference has been made. A brief statement of the results obtained by the latter method will appear elsewhere shortly,[1] while the full and detailed results of the whole investigation will eventually be issued by the Carnegie Institution of Washington in a special publication.

In carrying out experiments on the action of differential pressure with a view to reproducing more or less accurately the conditions of pressure which obtain in the deeper parts of the earth's crust, where flow is developed, it is manifestly quite useless to attempt to reproduce these conditions by simply submitting the materials to be investigated to compression in a testing machine, as is done in testing the strength of building stones. Differential pressure is certainly developed in such cases, but it consists merely of the ordinary atmospheric pressure on the sides of the test-piece while the enormously greater pressure exerted by the testing machine acts in the vertical direction. It is necessary to increase the lateral pressure and make it in some degree at least approach the measure of that exerted in a vertical direction if the pressure conditions of the zone of flow in the earth's crust are to be reproduced.

DESCRIPTION OF KICK'S METHOD

To secure this lateral pressure experimentally Kick[2] devised his method. This consists in making a box of some strong and at the same time ductile metal, such as copper, placing in it a specimen of

[1] See *Amer. Jour. Sci.* (June, 1910), and following numbers.

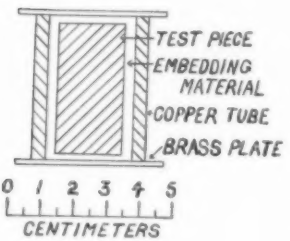
[2] "Die Principien der mechanischen Technologie und die Festigkeitslehre," *Zeit. des Ver. Deut. Ingen.* (1892), XXXVI, 919.

the material to be experimented upon, and then filling the space between the two with some embedding material which may be poured in as a liquid but which on cooling will solidify into a mass which is susceptible of deformation under pressure and which can, at the conclusion of the experiment, be removed by heat or in solution. The whole is then submitted to the action of a powerful press and squeezed down. The resistance to deformation offered by the copper as well as by the embedding material itself is transmitted through the embedding material to the specimen, which thus receives a very considerable amount of lateral support, or is submitted to a very considerable amount of lateral pressure as the deformation proceeds. After the completion of the experiment the embedding material is removed and the specimen recovered and examined. This method is easily followed, experiments can be made quickly, and but little mechanical skill is needed in preparing the materials for the purposes of the experiment. It can, however, be used only in experiments carried out at ordinary temperatures, and it is impossible in using it to determine accurately the pressure to which the specimen is being subjected, for the pressure is divided between the box, the embedding material, and the specimen itself. Furthermore, the pressures which are obtained by this means are not so great as it is desirable to employ in some cases. Kick, however, succeeded in this way in developing permanent deformation in rock salt, talc, gypsum, fluorspar, and marble. Two papers by Rinne,[1] which have appeared more recently and while the present investigation was being carried out, also present an account of certain experiments in which Kick's method was employed and in which rock salt, sylvine, and marble were deformed.

In the present investigation stout copper pipe was used, the standard size known as "one-inch iron-pipe size" being usually employed. This has an internal diameter of 1.063 inches and is made of material having a thickness of 1.125 inches. From this lengths were cut off to suit the specimen to be examined. The piece of tube, having smoothly finished ends, was placed in an upright position on a glass

[1] "Beitrag zur Kenntniss der Umformung von Kalkspathkrystallen und von Marmor unter allseitigem Druck," *Neues Jahrb. für Min.*, etc. (1903), I, 3, s. 160; "Plastische Umformung von Steinsalz und Sylvin unter allseitigem Druck," *ibid.* (1904), I, 3, s. 115.

plate and a portion of the embedding material (molten alum or whatever other material might be selected) was poured into the tube. The portion of the liquid which came in contact with the glass solidified almost immediately, forming a cake at the bottom, and the specimen to be compressed was then inserted into the still unsolidified upper portion of the liquid, in such a position that it would be compressed in the desired direction, and the rest of the embedding material was then poured in quickly so that it would mingle with that already contained in the tube before this had completely solidified. When quite cold and solid, this upper portion, often more or less porous on account of the air bubbles which it contains, was pared away with a knife or filed away by means of a large, coarse, flat file, till the surface was level with the end of the tube. A few smart taps then removed the glass plate from the bottom of the tube thus filled, leaving a flat and polished surface.



When putting it in the press, it has been found best to place over each end of the tube a piece of stout brass plate. Upon the application of pressure the copper tube is first pressed into this plate at either end and a very firm and solid joint is made, the tube becoming converted into a box, from which nothing can possibly escape unless the tube itself is ruptured. The copper tube with its contents ready to be squeezed down in the press is shown in the accompanying figure. In some cases larger and heavier copper tubes of various sizes were employed.

Four different embedding materials were used in these experiments, namely, alum, sulphur, fusible metal, and paraffine wax. All these can be rendered fluid at comparatively low temperatures. Kick employed the two materials first mentioned and he also in some cases used shellac and in others stearine. Each of these substances has certain advantages. On the whole, alum and paraffine wax have been found to be the most suitable and in the present series of experiments have been used in the majority of cases.

Alum, if employed, can readily be removed at the conclusion of the experiment by placing the deformed tube in hot water on a water bath for a short time. But it has the disadvantage when used as an embedding material for limestones, that, whether in a state of fusion or solution, it attacks carbonate of lime to a noticeable extent. On soaking out the contents of the tube with warm water at the conclusion of the experiment, however, a very distinct effervescence always ensues and this is especially marked if the marble has been rendered at all pulverulent. The amount of calcite which is thus dissolved is not, however, great but it is quite sufficient to etch the surface and destroy the polish of the marble or the transparency of the calcite crystal employed in the experiment. In the case of all the more resistant minerals and rocks, this objection of course does not exist.

When sulphur, fusible metal, or paraffine wax is used, these are removed at the close of the experiment by simply heating the tube in a deep porcelain dish, over which a second smaller one is inverted on a sand bath or a water bath as the case may be.

In order to get some clear idea of the resistance to deformation offered by these several embedding materials under the experimental conditions, a series of experiments was carried out on the deformation of copper tubes or collars of the size usually employed, some of which were left empty while others were filled respectively with the several embedding materials referred to above.

The following table shows the results obtained in tabular form. The values are given in pounds and each represents the mean of two closely concurrent experiments.

	Maximum Load Sustained	Excess of Resistance Due to Contents of Tube
Empty copper tube.....	23,250	.....
Copper tube filled with paraffine wax	23,800	550
Copper tube filled with fusible metal	29,925	6,675
Copper tube filled with sulphur.....	31,500	8,250
Copper tube filled with alum.....	34,450	11,200

It is seen in the first place that the copper tube when filled with paraffine wax offers but very little more resistance to deformation than does the empty tube. Under the conditions of the experiment

the paraffine wax develops but little internal friction and moves with comparative ease. With the other three materials the case is very different, a marked resistance being offered to deformation. This is greatest in the case of alum and least in the case of fusible metal. Subtracting the load required to deform the tube itself from that required to deform the tube filled with each substance respectively, it is found that the load required to deform the columns of the three materials in question (inclosed in the tubes under the conditions of the experiment) is that given in the last column of the table. These values calculated in pounds per square inch, using the area possessed by a cross-section of the columns of materials before deformation, which does not differ greatly from that possessed by the ends of the deformed masses, are given in the following table, together with the ratio of their respective strength or resistance which they offer to deformation, reduced to its simplest terms.

	Lbs. per Square Inch	Ratio of Strength
Paraffine wax	620.7	1.
Fusible metal	7533.9	12.13
Sulphur	9311.5	15.00
Alum	12641.1	20.36

In the case of a tube filled with paraffine wax, whenever the smallest fissure develops in the copper tube the inclosed paraffine passes out in the form of a thin, narrow ribbon and continues to issue as a long, graceful, curling band until the pressure is removed. When rupture takes place in a tube filled with alum the contents of the tube are not forced out until the crack has opened considerably, when the alum commences to fall out in a pulverulent condition. In the case of the fusible metal, on the other hand, the rupture of the inclosing tube does not lead to a discharge of the contents through the crack, but the copper tube peels off and the inclosed metal flattens down into a cake having a smooth, rounded surface. A striking fact noted in the case of tubes filled with sulphur is the continued sound of cracking which issues from the sulphur during deformation, a sound which resembles that produced when glass or any other brittle body is similarly compressed. At the conclusion of the experiment, however,

if the copper tube be sawn open the sulphur within is found to be to all appearances as hard and solid as any mass of sulphur could be, although in the mass, here and there, little surfaces can be detected which have a slight shimmer and which are evidently planes of slipping. The cohesion of the mineral along them, however, is to all appearances as great as elsewhere in the mass.

In connection with Kick's process there is one point of some importance to which attention does not seem to have been paid by those who have employed the process. This is the question as to whether, in carrying out the experiment, as the deformation of the cylinder goes forward, the pressure exerted on the specimen is conveyed to it entirely through the embedding material, or whether, in the latter stage of the compression, the specimen is actually nipped between the top and bottom of the tube or box which incloses it, that is to say, between the plates of the press, and is pressed upon directly by these without the intervention of any of the embedding material, or of a mere film which remains and which on account of its thinness exerts no influence.

Any experiment may be arranged so as to have the pressure exerted in either of the above ways, but no distinction seems to have been made between the two cases by former workers. As a matter of fact, however, very different results are obtained as one or other method of experimentation is adopted. If the specimen submitted to pressure continues throughout the experiment to lie entirely surrounded by the embedding material and is not pressed upon by the plates forming the ends of the tube, the value of the differential pressure to which it is subjected depends on the "stiffness" or viscosity of the embedding material, that is to say, on its internal friction. In the present state of our knowledge of the mathematics of plastic flow, it is impossible to calculate accurately the stresses set up in the inclosed specimen; although if movement is taking place in the embedding material the stresses are differential. When, however, the substance experimented upon offers great resistance to deformation, as for instance glass or porcelain, the differential stresses set up in any of the embedding materials hitherto employed are not, under the conditions of experimentation adopted, sufficiently powerful to bring about a deformation of the material. The alum, or whatever

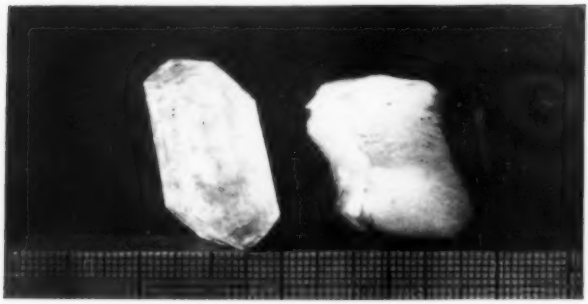
embedding material may be employed, flows around the specimen without producing any effect upon it. If an embedding material could be secured which under compression developed additional "stiffness," the required deformation of the substance might be secured, as when steel is used to inclose the specimen.

When, however, the length of the tube is so arranged that, after bulging has gone forward to a certain extent and the specimen inclosed in it has been submitted to the conditions above described, a point is reached when the top and bottom of the tube, backed by the press plates of the machine, come in contact with the specimen and commence to squeeze it between them, and a much more powerful vertical pressure is brought to bear upon the specimen. Under this, deformation is often produced in a specimen which cannot be obtained by the movements of the embedding material. It may happen, of course, that the vertical pressure thus exerted is relatively too great and the specimen breaks. This pressure, however, may be adjusted so as to yield excellent results.

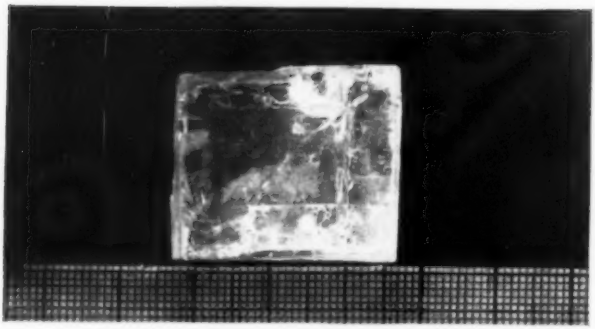
It seems clear that, under the experimental conditions which obtain in Kick's method, it is impossible to arrive at more than a general approximation in endeavoring to estimate the pressure to which the specimen is submitted. The pressure exerted by the machine is divided between the copper tube, the embedding material, and the specimen itself, and the resistance offered by each of these changes continually as the deformation proceeds. It is thus impossible properly to apportion the vertical pressure borne by each of the three elements, and when an attempt is made to go one step farther and estimate the lateral pressure exerted on the specimen by the material which incloses it, many additional and at present insuperable difficulties are encountered.

DEFORMATION OF CERTAIN MINERALS

As preliminary to the study of the deformation of rocks, a series of experiments was made on the deformation of rock-making minerals under differential pressure. A number of minerals possessing a progressively greater hardness were selected, with the view to obtaining a series of results, beginning with minerals which are known to be readily susceptible of plastic deformation and passing to others



(*a*) Selenite crystal before and after compression



(*b*) Rock salt crystal before compression

(*c*) Same crystal as in (*b*)—after compression

whose capabilities in this direction are as yet unknown and then to still harder minerals which are considered to be perfectly brittle, so far as this property is known to be possessed by any body in perfection. The mineral species chosen were for the most part those constituting Mohs's Scale of Hardness, although certain others were also included in the list. The series was as follows:

Name of Mineral	Hardness Mohs's Scale	Name of Mineral	Hardness Mohs's Scale
Selenite	2	Limonite	5–6
Rock salt	2.5	Orthoclase	6
Iceland spar	3	Magnetite	5.5–6.5
Fluorite	4	Pyrite	6–6.5
Apatite	5	Quartz	7
Diopside	5.5	Garnet	6.5–7.5

The same body would undoubtedly give different values for plasticity if tested in different ways, just as the same body gives different values for the breaking point, according to whether the latter is measured by bending, tension, or impact.

Speaking generally, however, under ordinary conditions of temperature, hardness is a function of plasticity and minerals become less plastic as they become harder.

Selenite.—A clear transparent crystal from Ellsworth, Ohio, was selected. It was perfect in form, being bounded by the prismatic faces in combination with the clinopinacoids and clinodomes. The crystal measured 1.246 inches (31.6 mm.) in the direction of the vertical axis, and 0.618 inch (15.68 mm.) in the direction of the ortho-diagonal axis. This was placed in a copper tube 1.75 inches (44.45 mm.) high and otherwise of the standard size commonly employed in these experiments, namely, having an internal diameter of 1.062 ($1\frac{1}{16}$ inches, or 26.98 mm.), the walls of the tube being 0.125 ($\frac{1}{8}$ inch or 3.175 mm.) thick.

The crystal was placed in the tube on end, as shown in Plate I, Fig. *a*, so that it rested on the lower solid angle, the line of the intersection of the clinodomes being inclined at a considerable angle to the plane of the end of the inclosing tube. Paraffine wax was used as an embedding material, since alum, sulphur, or fusible metal melts at temperatures above that at which selenite loses its water. The paraffine wax, melting at a temperature below that of boiling water,

was poured around the selenite crystals until the tube was filled, the usual precautions already referred to being observed, and a brass plate was placed on either end, when it was inserted in the press and served as a top and bottom to the tube. The pressure being gradually raised, a large ring-shaped bulge gradually developed near one end of the copper tube, and eventually the metal began to tear open at one point on this bulge. The pressure was then taken off, the tube removed from the press, the paraffine melted away, and the selenite crystal obtained. The crystal was found to have undergone a very marked deformation.

In order to obtain further deformation, the crystal was then placed in the same position in another tube, having the same diameter as that formerly employed but only 1.5 inches (38.1 mm.) high, and this, after the residual space had been filled with paraffine, was compressed in the same manner as before. In this shorter tube a further deformation of the selenite was secured. The maximum load employed was 24,000 pounds (10,872 kilos), and the total time during which deformation was actually going forward was 70 minutes. The selenite crystal, after removal from the tube, is shown in Fig. *a*, Plate I, there being placed beside it another crystal of the size and shape which it originally possessed. It will be seen that the acute solid angles of the monoclinic prism have been turned back by movement along a plane coinciding approximately in direction with an orthodome, while both ends have also been bulged out laterally and the whole crystal has also been slightly curved. There are no traces of fracture, tearing, or cleavage, but the surface of the crystal—more especially in those parts which are most deformed—is minutely wrinkled. The extremities of the crystal, where the deformation is most intense, have for the most part lost their transparency and are now translucent.

In the case of selenite, therefore, deformation under differential pressure can be produced readily and at comparatively low pressures. It is certain that in the case of the selenite crystal in question, a much greater deformation might have been secured by placing the crystal in successively shorter and wider copper tubes as each showed signs of rupture, and thus flattening it out by stages.

Rock salt.—A large cleavage cube of clear transparent rock salt

was taken. This measured 1.378 inches × 1.18 inches × 1.38 to 1.389 inches (35 mm. × 30.05 mm. × 35.05 to 35.3 mm.). It was inclosed in paraffine wax in a copper tube in the usual way. This was squeezed down until it showed signs of rupture when the salt crystal, now considerably flattened, was removed and placed in paraffine in another shorter but wider tube, which was in its turn squeezed down until rupture threatened, when the crystal was removed to a third and still wider piece of copper tube, in which the deformation was completed, the maximum load employed being 157,000 pounds.

The salt when removed was found to have the form of a continuous flat cake, nearly square in section. It now measured 0.56 inch (14.2 mm.) in thickness and was 2.215 inches to 2.25 inches (53.97 mm. to 57.15 mm.) by 2 inches to 2.125 inches (50.8 to 53.975 mm.) in diameter. Photographs of the crystal as it appeared before and after deformation are shown in Plate I, Figs. *b* and *c*. Although a solid mass, quite firm and hard, it had developed a series of fissures extending from both the lower and upper surfaces into the mass, these being wedge shaped in form and following the direction of the faces of the cube, i.e., running parallel to the longer sides of the flattened crystal. These fissures did not pass completely through the crystal from top to bottom, but often penetrated into it deeply. Neither were they continuous from side to side, but were interrupted and crossed each other at right angles. They were not seen on the narrow edges of the mass.

The deformed crystal of salt was brightly translucent but not actually transparent, and the sides of the flattened crystal were in several places beautifully curved. The remarkable plasticity of the salt not only is shown by the manner in which the crystal was flattened out, but is seen in a striking way where the cube, having been carried against the sharp incurving edge of the spreading end of the tube in one place, took an impression of the latter in the form of a deep, sharp-angled, and smooth-faced groove crossing the corner of the salt cube, the impression being as sharp as if it had been taken in wax.

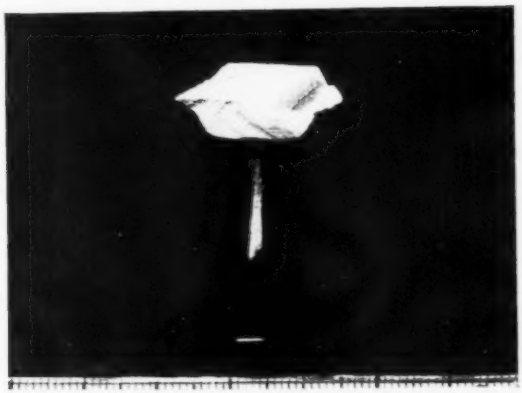
In the present case it was found inadvisable to carry the deformation of the salt any farther, since the little fissures mentioned above having once formed, the downward pressure forced the paraffine into them, and thus tended to divide up the salt crystal by a series of

paraffine wedges driven into it. Even in this case, the crystal would develop a filigree pattern; but if the conditions of the experiment be slightly altered so as to prevent the formation of the wedges of paraffine, it is believed that a salt crystal, on account of its great plasticity, might be flattened out to almost any required extent and might be molded into any desired form.

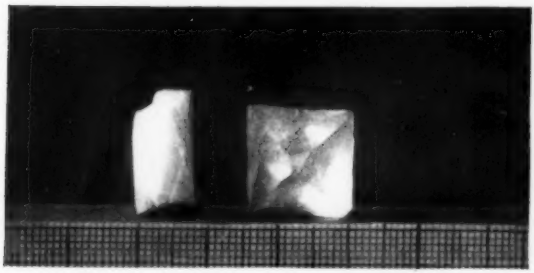
Iceland spar.—Since in considering the deformation of marble the effect of differential pressure on the constituent calcite grains is described, it is unnecessary here to repeat these descriptions. It may, however, be of interest to refer to a single experiment on the deformation of a large cleavage fragment of Iceland spar.

In this a cleavage rhombohedron of Iceland spar, measuring 0.73 inch (18.54 mm.) between the acute angles of the rhombohedron, was embedded in alum in a copper tube of the usual type, having a height of 1.25 inches (31.75 mm.), and a wall thickness of 0.125 inch (3.175 mm.), the tube being closed by a thick plate of cast iron placed against one end and a plate of machinery steel placed against the other, the rhombohedron being so set that its acute edges would come against the metal plates at either end as the deformation progressed. The tube was then squeezed down to a height of 0.473 inch (12.01 mm.), under a load of 83,000 pounds. On dissolving away the alum it was found that the calcite rhombohedron had been pressed into the metal plates at either end, leaving a faint but clearly perceptible impression on the machinery steel at one end and a somewhat more distinct one in the cast iron at the other. Neither of these, however, was so distinct as those produced by the fluorite (see below). The edges of the calcite which produced the indentations remained quite sharp and showed no granulation, but the crystal under the pressure has been converted into a perfect twin crystal, the plane of twinning being at right angles to the direction of maximum pressure (see Plate II, Fig. *a*).

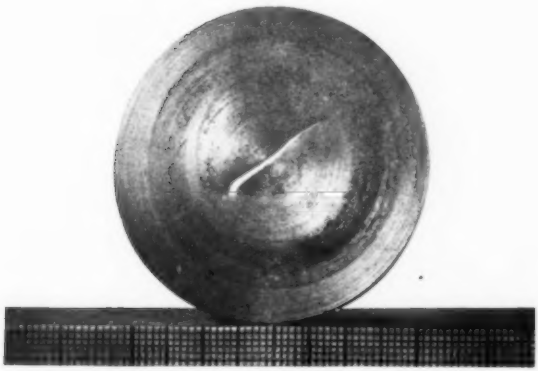
Fluorite.—Passing to the next higher member of Mohs's Scale of Hardness, the action of differential pressure on fluorite was investigated. Five experiments were made with this mineral. For the first, a group of twinned fluorite crystals, green in color and consisting of three interpenetrating cubes from Weardale, Durham (England), was selected, the largest of these crystals being 0.82 inch (20.8 mm.)



(*a*) Twin of calcite produced by compression



(*b*) Fluorite crystal before and after compression



(*c*) Nickel steel disk penetrated by the edge of a crystal of fluorite

in diameter. This was placed in a copper tube, 1 inch (25.4 mm.) high and otherwise of the same dimensions as those usually employed, namely 1.0625 inches (26.98 mm.) in internal diameter, and having a wall 0.125 inch (3.175 mm.) thick. Melted alum was used as an embedding material and a brass plate was used to form the top and bottom of the tube. The whole was then placed in the press and squeezed down until the tube was reduced to 0.75 inch (19.05 mm.) in height. When, this, having assumed a symmetrical bulge, commenced to develop minute fissures in its most distended portion, the experiment was brought to a close. The time occupied in the deformation was 50 minutes, the pressure being gradually raised until it reached a load of 42,500 pounds. On dissolving away the alum, the group of fluorite crystals was obtained as a firm coherent mass, but the deformation had been so great that while portions of two cubes could be recognized, the rest of these two cubes and the third cube had been so welded together into a lump that it was impossible to distinguish them or to ascertain which part of the mass they represented. The green color of the original mineral had disappeared except in one or two spots, and its place had been taken by a pale violet tint, and the mineral, which was originally transparent to translucent, had become practically opaque.

A thin section of the deformed mass was then prepared, which, when examined under the microscope, showed that the fluorite was still clear and transparent, except along a few lines which traversed the slide in sinuous curves. Here the mineral presented a turbid appearance. The three individuals composing the mass were seen to be traversed by their respective cleavage lines, evidently developed in grinding the section, which made it possible to determine their boundaries in a general way. Each cleavage line was seen to follow a straight course, until it approached the turbid lines above mentioned, when it bent with a sharp curve or sudden twist; the crystal along these lines where the movement was greatest being broken into a mass of minute grains, still, however, firmly coherent. When examined between crossed Nicols the fluorite was seen to remain perfectly isotropic, except along the lines of most intense movement and granulation, where it can frequently be seen to be distinctly doubly refracting.

It is thus evident that the mineral fluorite is plastic to a marked degree. It may be bent and twisted without any signs of disruption and it is only along certain lines of very intense movement that the mineral breaking develops a cataclastic structure, just as marble does in places when deformed under low differential pressures. The little broken grains of fluorite thus produced, however, as in the case of the marble, remain firmly coherent, and it is highly probable that, as in the case of marble, if the deformation were carried on under much higher pressures or at a higher temperature, fluorite could be deformed without any fracture or the development of any cataclastic structure whatsoever.

While, however, the plasticity of the mineral is remarkable, its resistance to movement and the force required to bring about its deformation appear to be considerably greater than in the case of calcite, and it was observed that an angle of one of the fluorite crystals which cleared itself from the alum and came into contact with the brass plate at one end of the tube made a distinct triangular depression in it.

Several other experiments with a perfect cleavage octahedron of fluorite from Westmoreland, Cheshire Co., New Hampshire, carried out under identical conditions, resulted in the flattening of the rhombohedron, the movement being of the nature of a plastic flow, except possibly where here and there a few little opaque white lines indicated the development of a minute cataclastic structure. In these experiments also the fluorite showed the same stiffness or resistance to deformation, which was seen not only in the very high pressure required to deform it, but also in the fact that as the copper tube was squeezed down and the alum flowed away from above and below it, leaving the mineral in contact with the brass plates at either end, the octahedral faces of the mineral, where they came upon the brass plate below, sank into it, leaving a well-marked depression, while the two octahedral edges bounding the face in contact with the upper brass plate, which was 0.075 inch (1.9 mm.) thick, cut completely through it, leaving a wide rent, and having passed through this plate, forced their way into a second brass plate behind it.

Another experiment employing much higher pressures was then made by taking an octahedron of fluorite, similar to that employed

in the last experiment, and inclosing it in alum in a piece of thicker copper tube. This tube was 0.75 inch (19.05 mm.) high, and made of metal 0.187 inch (4.65 mm.) thick. The octahedron was set in the alum so that it rested on an edge. For the ends of the tube, instead of brass plates, plates of steel were used. That at the bottom of the tube was made of machine steel one inch (25.4 mm.) thick, and that at the top was a plate of nickel armor steel 0.063 inch (1.6 mm.) thick. The tube was slowly squeezed down to a height of 0.384 inch (9.75 mm.). This occupied 30 minutes, the load finally reaching 112,000 pounds (50,804 kilos). The fluorite octahedron was found to have been squeezed into a nearly square tabular mass (Plate II, Fig. *b*) measuring about three-quarters of an inch across, the movements being of the same nature as those described in the last experiment. Crossing the top and bottom of this mass diagonally were two faint ridges representing a survival of the edges of the octahedron. These by the pressure had been brought into contact with the steel plates at either end of the tube and had actually embedded themselves in the latter, the upper and sharper edge sinking into the nickel steel, leaving a deep, well-marked depression in the steel along its whole length (Plate II, Fig. *c*), and at the same time distinctly bending the plate. The lower edge, which was blunter, left a similar depression in the machine steel below. These edges of the fluorite crystal, although having in this way forced themselves into the steel, showed no signs of breaking or granulation, but were intact. It would without doubt be possible, by changing the conditions of the experiment somewhat, to force a crystal of fluorite completely through a piece of steel armor plate.

As in the other experiments, the color as well as the form of the mineral was found to have been altered by the pressure. Two of the opposite solid angles of the octahedron still retained a green color though much paler than before, but the rest of the flattened crystal, including the edges which had embedded themselves in the steel, that is to say, that portion of the mineral which had been submitted to the most intense pressure, was found to have assumed a distinct violet or purple color.

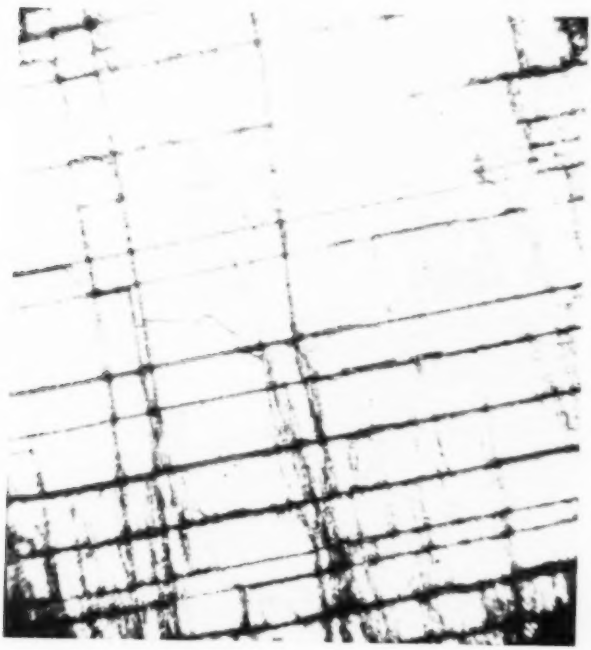
Another experiment, in which paraffine wax was used instead of alum as an embedding material, showed that with this medium a

similar distortion of the fluorite was produced while the green color of the original mineral became much paler. The change in color of the fluorite which, as noted above, was produced in every instance by the pressure is a very curious phenomenon. In three of the experiments the change consisted in the substitution of a much paler tint of green for the deeper green color which the mineral possessed originally. In the other two cases, where the deformation had been if anything more intense, the original green color actually changed to pale purple or violet, a color which is often possessed by the fluorite from Derbyshire and elsewhere. The reason for this change is unknown and will probably remain so until the nature of the fugitive colors displayed by this mineral have been discovered. It was at first thought that the change in question might have been brought about by the heat of the molten alum in which the mineral was embedded and that it might thus have been induced before the pressure had been applied. Crystals of the fluorite from both localities were accordingly taken and embedded in molten alum in the usual way, but it was found on removing the alum by solution that no change in color whatsoever had resulted from this treatment. The change in color therefore must be due solely to the action of pressure.

Apatite.—A small crystal of opaque greenish apatite from one of the Canadian localities, probably in Ottawa County, Quebec, measuring a little less than 1.25 inches (31.75 mm.) in height, and about 0.5 inch (12.7 mm.) in diameter, was selected. The crystal showed the usual prismatic and pyramidal faces seen in the specimens from this district, as well as small basal planes. It was placed, resting on one of the pyramidal faces, in a copper tube of the same dimensions as that employed in the last experiment, but 1.25 inches (31.75 mm.) high. The tube was then filled up with molten alum in the usual way and brass plates were placed at either end. The whole was then slowly squeezed down until the tube showed signs of rupture, the time occupied by the deformation being 55 minutes and the maximum load being 43,000 pounds (19,405 kilos).

On dissolving away the alum the apatite crystal was found to have been crushed to a coarse powder at either end. The central part—representing about one-half of the original crystal—however, remained as a solid mass, and showed portions of the six prismatic faces. Crossing

(*a*) Microphotograph of a thin section of a diopside crystal before compression. Between crossed Nicols



(*b*) Microphotograph of same, after compression. Showing the development by the pressure of polysynthetic twin lamellae

this remnant of the crystal approximately parallel to a pyramidal face, and thus in a direction approximately at right angles to the direction of pressure, some half-dozen planes could be seen along which movement of the nature of a minute faulting had taken place. The mineral, however, was firmly coherent where traversed by these planes, indicating that apatite under the experimental conditions, although breaking along certain lines, was firmly welded together again by the pressure and was thus slightly plastic. A further evidence of plasticity is afforded by the fact that one of the prismatic faces shows a slight but distinct bending or curving.

The evidence afforded by the experiment, therefore, shows that while apatite is very much more brittle than the softer minerals of the series, it nevertheless possesses the property of plasticity in a slight degree at least, a conclusion which is confirmed by the occasional discovery of apatite crystals which are distinctly curved or bent in the highly contorted crystalline limestones and associated rocks of Laurentian age in the Ottawa district. That the mineral is, however, but slightly plastic even under the conditions of very great pressure which obtain during the contortion of the limestones above mentioned, is shown by the fact that the curved crystals to which reference has been made are always found to be broken when the bending becomes very pronounced.

Diopside.—A number of clear crystals of pale green diopside from De Kalb, New York, were secured, and from these two were selected. These, together with an octahedron of magnetite from Mineville, New York, were embedded in alum, inclosed in a copper tube, and submitted to pressure in the usual manner adopted in Kick's method. The copper tube was 0.877 inch (22.29 mm.) high, but otherwise of the same dimensions as that employed in the case of apatite—the experiment being carried out in the same manner. The diopside crystals were quite transparent and showed both pinacoids, the prisms, two sets of domes, and one set of pyramidal faces. One of these crystals was placed in the tube so as to lie upon its orthopinacoid, the direction of the pressure being consequently at right angles to this face; while the other was placed so that the pressure would be exerted upon it in a direction as nearly as possible at right angles to the base. The pressure was continued until the copper tube commenced to show

signs of rupture, the time occupied by the experiment being about one hour, and the load finally rising to 48,000 pounds (21,773 kilos). On removing the test from the press, it was found that the end of one crystal of pyroxene was protruding slightly from the alum and had sunk into the brass plate, leaving a distinct impression in it; and, on dissolving away the alum, it was found that both pyroxenes displayed a twinning parallel to the base which had been developed in them by the pressure; this being strikingly seen in the case of the crystal which was compressed approximately in a vertical direction. The twinning in the case of this crystal appeared as a series of little parallel lines crossing the lateral faces in the direction of the base, and in appearance resembling closely the basal parting so frequently seen in pyroxenes which occur in the limestones of the Grenville series and other rocks which have been submitted to great compressive stresses.

A section was then cut through this crystal in a vertical direction. Under the microscope, between crossed Nicols, this was found to be so orientated as to intersect the crystal in a direction between the orthopinacoid and a prismatic face. The prismatic cleavages were well seen and a second set of interrupted cleavages crossed these at right angles or nearly so, being parallel to the base. Parallel to these latter was a beautiful series of clear, sharply defined, polysynthetic twin lamellae, which had been developed by the pressure. The section was 14 millimeters wide, and in this width displayed 140 twin lamellae, each of which was wide enough to show clearly its individual character, the series being spaced at nearly equal distances across the crystal. Their appearance under the microscope is shown in Plate III, Fig. *b*, while Plate III, Fig. *a*, shows the apearance of a section of the original pyroxene. Apart from the twin lamellae, the mineral shows a slightly undulating extinction, and the section is crossed in one or two places by narrow lines of granulated material, along which, under the pressure, the mineral has broken with the development of a cataclastic structure. A study of the section shows that probably the twinning was first developed and that the mineral under further pressure broke along certain lines. The partial loss of transparency observed in the deformed crystal is largely due to the development of similar lines of broken material, especially at the

ends of the specimens where this loss of transparency is most pronounced.

It is thus evident that under the differential pressure the diopside crystals became slightly twisted, and then, as the pressure increased, changed their shape somewhat by the development of a series of polysynthetic twin lamellae, finally breaking along certain lines, with the development of cataclastic structure. In a paper published in 1886, Mugge[1] describes some experiments which he carried out on the behavior of diopside under pressure. He inclosed clear and untwinned crystals of this mineral in lead and then squeezed the mass down by means of a powerful screw press. In some cases he found that the mineral was reduced to a powder, and in other cases the crystal survived, but, even after repeated trials, he was unable to induce any twinning in it. In some few cases, in the partially crushed crystals, he found what was apparently a twinning parallel to the base. He states, however, that he could very rarely get a section of the twinned material so thin and with the lamellae so broad that the individual lamellae showed their own optical orientation, their existence being indicated merely by the fact that between crossed Nicols the extinction was never complete. It is possible, however, as above described, by employing Kick's process, to obtain in diopside a perfect twinning, in which clear, well-defined lamellae extend through the whole individual and are identical in character with those seen in the twinned diopsides found in crystalline limestones which have been subjected to orogenic movements.

Limonite.—A cube, pseudomorph after pyrite, from a locality in Virginia was selected. It was treated in precisely the same manner and in a tube of the same thickness as in the case of the apatite and diopside. On dissolving away the alum, the cube of limonite was not found to present any distinct evidence of plastic flow. Its lower surface was intact except for the presence of a minute crack. The upper surface was traversed by many minute open fissures which crossed one another, giving rise to a rudely rectangular pattern. Each rectangle formed the base of a wedge of the material which was driven downward, causing the sides of the cube to slant outward.

[1] "Ueber künstliche Zwillingsbildung durch Druck am Antimon, Wismuth und Diopsid," *Neues Jahrbuch für Mineralogie* (1886), I, 183.

It is evident in this case that while there may have been some slight plastic deformation in portions of the cube, the movement has been essentially one which has taken place along planes of fracture.

Orthoclase.—The crystals used in this experiment were from Good Springs, Lincoln County, Nevada. They were of simple form and very symmetrical development, being bounded by the clinopinacoids, the basal faces, and the unit prisms.

Three of the crystals were placed together in the same copper tube, one lying on a clinopinacoid, one on a prismatic face, and one on its basal plane. The experiment occupied one hour and forty-five minutes. Alum was used as the embedding material and the maximum load—which was of course that reached at the conclusion of the experiment—was 195,000 pounds (88,455 kilos). As the compression slowly proceeded, faint cracking sounds were frequently heard from the interior of the tube. On removing the brass plate, the outlines of the crystals could be seen in the alum at either end. At one end they were for the most part still covered by a thin film of alum, while at the other end they had been forced into the brass plate, deeply indenting it; while one of the crystals, in which a sharp edge came against the brass plate, had forced its way through this plate, tearing it completely open. These portions of the crystal in contact with the brass plates showed no signs of fracture. On dissolving away the alum, however, all three crystals were found to have been much crushed in places.

The crystal which lay upon the prismatic face still held together but was traversed by several little fissures which had their courses chiefly parallel to the base and to the clinopinacoid, that is, in the direction of the normal cleavage of the mineral. They did not, however, invariably follow these planes, but in some cases ran irregularly across the crystal. The individual which lay upon its clinopinacoid had crumbled to pieces. The largest of these pieces showed little cracks parallel to the base and to the clinopinacoid and others running in the direction of the orthopinacoid. The crystal which rested upon its basal plane was reduced to a mass of little fragments without definite form.

Two thin sections were prepared from the first and second of the crystals respectively, in order to ascertain whether any further evi-

dence as to the character of the movement which had taken place could be obtained by a microscopic study of the crushed mineral. The sections in both cases were cut parallel to the orthopinacoid, while, for purposes of comparison, a third section running in the same direction was prepared from one of the original uncrushed crystals. Under the microscope the crystals which had been subjected to compression were seen to be traversed by a number of minute cracks, and also showed in the much-crushed portions faint strain shadows, when examined between crossed Nicols. It is evident, therefore, that under the conditions of the experiment, the orthoclase, while probably displaying a very slight plastic movement of the nature of twisting, as shown by the slightly uneven extinction produced by the pressure, moves almost entirely by fracture and granulation. This agrees with the deportment of orthoclase as observed in highly deformed rocks in the earth's crust, the mineral in these rocks being usually granulated or recrystallized under conditions of differential pressure.

Magnetite.—A perfectly symmetrical octahedron of this species from Mineville, New York, was, as mentioned above, embedded in alum and submitted to pressure, with the diopside crystals whose behavior has already been described. On dissolving the alum, the magnetite was found to have been broken to pieces, the fragments having the form of little plates which had separated from the crystal parallel to the octahedral faces.

Pyrite.—The pyrite employed was from the Saratoga Mine, Gilpin County, Colorado. The fragment selected had the form of a half cube, showing the crystal faces, with a surface of fracture on one side. The specimen, with the edge of the cube upward, was embedded in alum in a copper tube with a brass plate at either end. Pressure was then applied, the deformation of the tube occupying 17 minutes, and the maximum load attained being 43,000 pounds (19,404 kilos). No sounds whatever issued from the tube as the deformation went forward. On removing the highly bulged tube from the press, it was found that the edge of the pyrite crystal, referred to above, had passed completely through the brass plate and had cut into the iron head plate of the press, the edge, however, remaining practically intact. On dissolving away the alum, it was found that

the lower portion of the crystal, still embedded in the alum, had been much crushed, the original crystal being now represented by one large fragment and a considerable quantity of fine powder. The pyrite, therefore, was crushed without showing any trace of plastic deformation.

Quartz.—A clear transparent individual of rock crystal from Hot Springs, Arkansas, was selected. It was embedded in alum in the usual way in a copper tube. The crystal was placed in a somewhat slanting position in the tube, so that it stood approximately on a pyramidal face. The pressure was raised gradually and the load used was just sufficient to start and maintain a very slow bulging of the tube. The pressure was continued for an hour and twenty minutes, by which time the height of the tube had been reduced to 1.37 inches (34.8 mm.), the maximum load employed being 34,000 pounds (19,404 kilos). Once only during the deformation was a faint cracking sound heard in the tube. On removing the alum, the quartz crystal was found to be still coherent with the exception of a few little fragments which had broken off from one end. The crystal, however, was traversed by a large number of cracks following directions approximately parallel to the rhombohedral faces, many of them not passing completely through the crystal, but running only a certain distance and being intersected by others crossing them. It is known that quartz when heated and suddenly cooled develops a tendency to rhombohedral cleavage; but it is also true that when a rigid or an imperfectly plastic body is submitted to pressure it tends to shear along planes which cross one another at an angle approximating to 90°. Whether in this case a tendency to movement along rhombohedral planes was developed, or whether the movement is one quite independent of crystallographic considerations, is uncertain. There was certainly, however, no indication of plastic flow.

Garnet.—The last mineral examined, being also the hardest, was garnet, a perfect rhombic dodecahedron of almandine from Bödo, Norway, being selected. It was embedded in alum in the usual manner, the whole being inclosed in a copper tube. The deformation of the tube occupied 50 minutes and the maximum load required was 175,000 pounds (79,383 kilos). A slight cracking sound was emitted at times as the experiment was going forward. On dissolving the

alum, the greater part of the crystal was found to have been reduced to a fine powder. There were a few larger fragments surviving but these showed no signs of distortion. The fragments when examined between crossed Nicols were found to be perfectly isotropic. The garnet, in fact, had been crushed and displayed no traces of plastic deformation.

DEFORMATION OF ROCKS

Seeing, as has been shown, Kick's method is not adapted for the development of plastic deformation in materials which are very hard, the rocks selected for examination were chiefly of the softer kinds, marbles, limestones, and dolomites of different varieties. The harder rocks were, however, represented by a typical granite. In these experiments columns of the rock were usually employed. These were 1.575 inches (4 cm.) long and usually 0.787 inch (2 cm.) in diameter, with a smooth and generally a polished surface. The copper tubes employed were somewhat larger than the column so that the alum might completely inclose the latter, and had an internal diameter of 1.06 inches (27 mm.) and a wall thickness of 0.125 inch (3.175 mm.). In some cases, as will be mentioned, cubes, prisms, and spheres of the rock were also deformed.

A. MARBLE: CARRARA, ITALY

This is the same white statuary marble which was employed in a former investigation and described in a former paper.[1] In the case of the large spheres, however, a somewhat commoner variety from the same locality was employed, since blocks of the statuary marble of requisite size for the preparation of these spheres could not be obtained.

1. COLUMNS

Columns of the marble were first used and the effect of various kinds of embedding material was studied.

(*a*) *Deformation with paraffine as an embedding material.*—The maximum load required for deformation of the tube with its inclosed

[1] F. D. Adams and E. G. Coker, "An Investigation into the Elastic Constants of Rocks, More Especially with Reference to Cubic Compressibility," *Carnegie Institution of Washington, Publication No. 46* (1906), 26.

marble and embedding material in these experiments was 30,500 pounds.

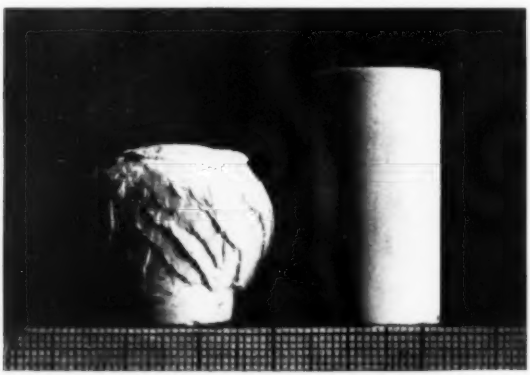
The column after deformation, when removed from the paraffine, displays a very characteristic shape, and one which is quite different from that shown by the rock when deformed in alum. The movement set up in the column commences at one end and gradually extends toward the other end of the column, not however as a general rule reaching this before the experiment has to be brought to a close on account of the impending rupture of the copper tube.

This movement results in the development of a symmetrical enlargement of that part of the column affected, the greatest diameter being a short distance from the end of the column. The deformed portion of the column thus swells out into a more and more pronounced bell-shaped form, which fades away into the unaffected portion of the column, which latter retains not only its form but also the original polish of the surface.

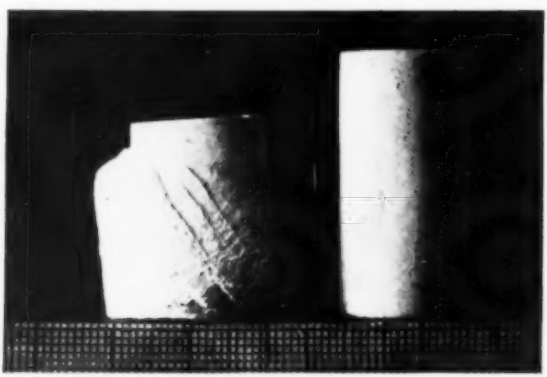
Crossing the smooth, bell-shaped surface, in that portion of the column in which movement has taken place, are certain faint lines which when the deformation is slight are just barely perceptible, but which become more pronounced as the deformation increases. These lines, which are uniformly spaced, or nearly so, are due to a very slight displacement along their course and are, as is well known, developed when any solid body is strained above its elastic limit. They are known as Cooper's or sometimes as Luder's lines. As seen on any one part of the lateral surface of the cylinder, they are arranged in two series which cross one another at an angle which, as nearly as it can be measured by an application goniometer, is 72 degrees. That is to say, each line makes with the vertical, which is the direction in which the pressure is applied, an angle of 36°. Along this multitude of intersecting planes, in the early stage of deformation, movement takes place with approximate uniformity, and as a result the cylinder slowly shortens, widening at the same time as described into a symmetrical, bell-shaped form which tapers down into the undeformed portion of the cylinder.

As the deformation goes forward and becomes more pronounced the movement, while still taking place simultaneously along a great number of these planes, becomes more pronounced along certain of

(*a*) Column of Carrara marble before and after deformation—using paraffin wax as an embedding material



(*b*) Column of Carrara marble before and after deformation, using alum as an embedding material



(*c*) Column of Carrara marble before and after deformation, using alum as an embedding material

them, so that, with the lateral expansion or bulging of the cylinder, there is combined a tendency for a portion of the cylinder to move more rapidly along some one plane, developing a specially pronounced shear in this direction. No rupture ensues, but the more pronounced movement in this direction is evident from the form of the distorted cylinder. This is shown in Plate IV, Fig. *a*, where the traces of such planes bound a V-shaped projection on the front of the deformed column. On the base or end face of the bulging portion of the cylinder, the lines above described are not seen, unless they be represented by a series of little, somewhat irregular radial fissures noticed where the deformation is very pronounced.

One noteworthy fact observed in every case where a cylinder of the marble was deformed in paraffine is that the column on removal of the paraffine is found to be cracked or fractured transversely, that is, in a direction at right angles to the axis of pressure. This is seen in Plate IV, Fig. *a*, where two of such fractures parallel to one another were developed in the same cylinder. The surface of such a fracture plane is approximately flat but not absolutely smooth or polished, and in partially deformed cylinders it frequently occurs just about the line between the deformed and undeformed portion. The same planes of transverse fracture are developed, upon the relief of pressure, in very strong fine-grained limestones when they are deformed in steel tubes. It is apparently connected with the elastic expansion of the rock on the removal of stress.

The invariable presence of this transverse fracture makes it impossible to determine the strength of the deformed column in compression. While probably not so strong as the original marble, it is still firmly coherent and hard, withstanding a sharp blow without breaking. When the deformation is pushed to an extreme, in addition to the Luder's lines, a series of faint, slightly wavy lines, running in a horizontal direction across the column and hence in a direction at right angles to the pressure, is developed.

When a section of the deformed marble is examined under the microscope, the decrease in transparency of the rock as compared with the original marble at once arrests the attention. This, on close examination, is seen to be due to the development of an immense number of twinning lamellae in the constituent calcite grains, often

in two or more sets crossing one another. These lamellae are very narrow, often taxing the power of the microscope to resolve them, but there is scarcely a calcite individual in the slide which is not crowded with them. It is thus evident that every individual grain in the rock has been affected by the movement and has changed its shape to a greater or less extent. When, however, the marble has been very highly deformed, movement is also seen to have taken place by granulation of the rock. In any single section the granulation has a tendency to develop along two intersecting planes, but as the deformation becomes more pronounced, the two series tend to converge and follow a more nearly horizontal course, and a single little line of granulation can often be seen to follow a minutely zigzag line running alternately in the direction of one series and then of the other, the resultant course of the line being transverse to the column and at right angles to the pressure. In this way the deformed column tends to break transversely with a slightly uneven surface, as mentioned above. It is to be noted that the marble does not show any tendency to develop a cleavage except in a direction at right angles to the pressure.

b) Deformation with fusible metal as an embedding material.—A column of the marble was then deformed, using fusible metal as an embedding material. The column and tube were of the same dimensions as in the experiments just described and the load required for maximum deformation was 35,000 lbs. The surface of the marble after deformation was found to be lusterless and displayed none of the intersecting lines seen when the rock is deformed in paraffine. The deformed column resembled in shape certain of the columns deformed in paraffine, but the rock itself was converted into a uniform chalky looking material which was much more friable than the marble deformed in paraffine. The mass was soaked in balsam, and thin sections were prepared from it. These, when examined under the microscope, were found to present essentially the same characters as in the case of the marble deformed in paraffine and just described. The twinning, however, was less marked and the granulation more pronounced.

c) Deformation with sulphur as an embedding material.—A column of marble of the same dimensions as before was then deformed

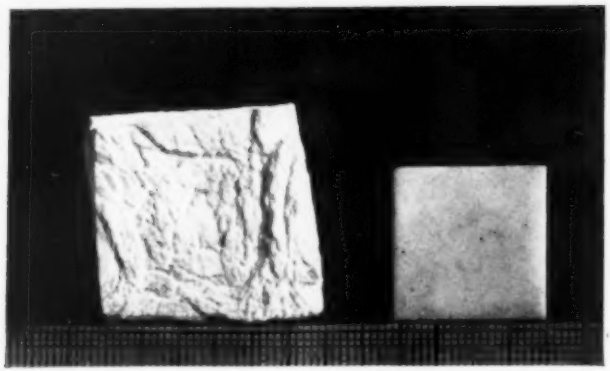
in a copper tube, also of the same dimensions as that employed in the experiments just described, but with sulphur as an embedding material. The deformation required a load of 37,500 lbs. (17,000 kilos). When the sulphur was melted away from the marble, the deformed column was found to be hard and solid, and to have been reduced in height from 1.561 inches (39.65 mm.) to 1.145 inches (29.09 mm.), a shortening of about 27 per cent. Its shape was striking, for one half of the column had sheared down over the other half, the plane of shearing making an angle of 36° with the vertical, which was the direction of pressure, and an angle of 54° with the horizontal, which is the same angle as that observed in the case of the lines traversing the surface of the marble when deformed in paraffine. This shearing movement did not take place on a single plane, but on a series of planes parallel to one another, or nearly so, and close together, giving rise to exactly the same structure as that seen in the "sheeted veins" or "shear strips" of many mining districts, as for instance at Cripple Creek. It is an excellent example of a distributed fault. The second series of lines seen in the paraffine experiments are here faintly indicated in a few places. There are no signs of rupture to be seen in the deformed column. The surface is nearly smooth, its only unevennesses being due to slight projections along the line of some of the planes constituting the distributed fault.

A series of thin sections was prepared, passing through the deformed column in a vertical direction. Under the microscope it is seen that there has been a slight movement throughout the rock, as indicated by the presence of a fine polysynthetic twinning in almost every calcite grain. This, however, has not been sufficient noticeably to flatten the grains in any direction. The chief movement is along the planes of shearing and is accompanied by a minute granulation, with the development, in many cases, of a microscopic breccia along the planes in question. The lines of shearing as seen under the microscope are not perfectly straight, but while maintaining a generally uniform course often have numerous little anastomosing branch fissures running parallel to them and occasionally crossing from one shear plane to another. The shearing thus takes place along a strip of the rock instead of in a single plane, and this strip is thus filled with a minute calcite breccia. The appearance under the

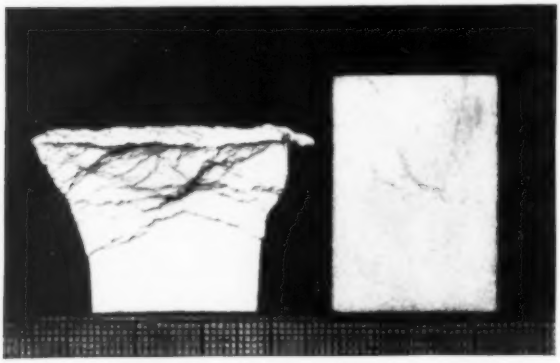
microscope is exactly that presented on a large scale by many fault planes.

d) *Deformation with alum as an embedding material.*—As has been shown, alum is much more resistant to deformation than either paraffine, fusible metal, or sulphur. A series of marble columns was accordingly deformed by Kick's method, employing alum as an embedding material. These were of the same dimensions as before, as were also the copper tubes employed. The maximum loads employed in the several experiments were from 35,000 lbs. to 41,500 lbs. The time of deformation was from 15 to 45 minutes. The shape presented by the deformed marble column is remarkable. The column for some distance from either end, in the earlier stages of deformation, remains intact, and these terminal portions are forced toward one another and into the middle portion of the column, which bulges outward, not however with a smooth symmetrical outline but with the development of a curious leafy form, which, when looked down upon from the end of the column, bears a resemblance to an artichoke. The leaves which wrap closely around the central stalk have well-developed, wedge-shaped points or terminations and occur in great numbers. They, however, are not arranged in regular series but each individual leaf has the appearance of overlapping others which lie beneath it. One of these curious forms is shown in Plate IV, Fig. *b*, with a column of marble of the original dimensions placed beside it.

When a vertical section is cut through the axis of one of the deformed columns, the undeformed ends of the column are seen to terminate within the substance of the column in the form of rather obtuse cones pointing toward each other, and these, under the pressure, slowly advance toward one another, thin layers of the marble shearing off their faces and being forced outward, thus causing the lateral expansion of the column under deformation. As this continues, the cones at either end become gradually sheared away, and when deformation is very far advanced they eventually disappear. Each little layer of marble, however, as it is sheared off the face of the cone in the line of a tangent to it, becomes cut across by planes of movement along which other layers are being sheared off in the direction of other tangents, so that the whole medial portion of the column



(*a*) Cube of Carrara marble before and after deformation



(*b*) Prism of Carrara marble before and after deformation

(*c*) Sphere of Carrara marbel after deformation

is slowly forced outward, moving along a complicated series of intersecting planes of shearing, which gives the diamond or leaf-shaped pattern on the surface of the deformed column.

In some cases where the deformation of the tube has been less symmetrical the upper portion of the column is found to have sheared down over the lower portion, the movement being concentrated along a series of parallel planes forming a sort of distributed fault, the rock, however, still retaining its continuity and being free from fissures (Plate IV, Fig. *c*).

When a thin section of a column which has been deformed in alum is examined under the microscope, all the individual grains of calcite are found to exhibit polysynthetic twinning, showing that they have all been more or less deformed, but as before, the chief movement in the rock is seen to have taken place along planes of shearing which traverse the rock and whose course is indicated by little lines of granulated calcite. In order to ascertain the strength of the marble after deformation, two of the deformed columns were tested in compression. They crushed at loads of 750 lbs. and 850 lbs. respectively, while a column of the original rock has a crushing load of 4,380 lbs. The deformed marble, therefore, while firm, is much weaker than the original rock.

2. CUBES, SQUARE PRISMS, AND SPHERES

In other experiments cubes, square prisms, and spheres of the marble were deformed. In one of these a cube nearly an inch on each side was by compression in three successive copper tubes reduced to a flat cake measuring 1.36 inches by 1.38 inches and 0.55 inch thick. The maximum load employed was 219,500 lbs., or approximately 110 tons.

This deformed cube was still hard and solid and showed no traces of a pulverulent character. It is clear from its form that the movements which it has undergone are identical in general character with those which developed the artichoke structure in the case of the marble columns. On the sides of the cubes two sets of intersecting lines, along which shearing has taken place, are seen. This shearing is most pronounced at the corners of the block which tend to shear down in pieces having approximately the form of the "leaves" of the

artichoke above mentioned. On the upper surface of the flattened cake a large number of lines are seen which follow rude polygonal and more or less concentric curves around the center of the surface, which mark the borders of areas differing slightly in elevation. There are also a few vertical lines running outward toward the corners. These areas outlined on this surface are bases of rudely wedge-shaped forms which moved downward and outward. Thus the whole mass flattened out (Plate V, Fig. *a*).

A series of experiments was then made using prisms of Carrara marble. In the first of these a prism 1.575 inches high and 1.1 inches in diameter was embedded in alum in a copper tube, and the whole was squeezed down under a load of 113,000 lbs. In this experiment the tube, while retaining its original diameter at one end, spread out under the pressure at the other, and the marble column developed a graceful, rectangular, bell-shaped form, ornamented by the same beautiful pattern of triangular leaves around the end where movement had taken place. The height had been reduced to 1.2 inches (Plate V, Fig. *b*).

In the others the inclosing tube bulged at the middle in the usual manner and yielded shapes like that of the column in Plate IV, Fig. *b*, in which the zone of maximum movement was in the center of the column, which was therefore ornamented by a frill of leaflike forms in low relief. In these the load required for deformation ranged from 133,000 to 197,000 lbs., the prisms being reduced in height from 1.575 to from 1.1 to 1 inch

A number of spheres 1.5 inches in diameter were then deformed in heavy copper tubes. By the movement the spheres were flattened to spheroids of wonderful form and beautifully ornamented, around the zone of maximum movement, by a garland of the same graceful leaflike shapes already described. The shearing which developed these spheroids is exceedingly complicated, layer after layer of the marble passing outward along the zone of maximum movement and upward toward the axes of the spheroids, each partially overlapping the one beneath, as shown in Plate V, Fig. *c*. The resulting spheroidal mass, however, is a hard, solid body of marble and shows no tendency to break in one direction rather than another. The movements, although concentrated along certain planes, do not take

place in planes of fracture, for the rock remains intact. The movement is that of a very stiff but nevertheless plastic mass.

In all the experiments just described the marble was completely surrounded by the embedding material. As the experiment proceeds, however, this flows away from about the top and bottom of the column or sphere where the pressure is greatest, and the rock is thus really caught between the upper and lower press plates of the machine, great lateral pressure however being at the same time exerted by the alum and its inclosing copper tube, and the conditions of differential pressure being thus secured.

Other experiments, however, show that a certain, though less pronounced, deformation will be produced if the marble remains in the middle of a mass of alum and is submitted only to pressure exerted by the moving alum itself, so that, if the differential pressure be of a high order, the harder limestone will be deformed by the movement of the surrounding but relatively softer matrix, provided there is not too great a difference in the relative stiffness of the two.

As a matter of interest an experiment was made to ascertain whether it would be possible to drive a nail through a mass of marble, under conditions of differential pressure such as those described above. A short nail, 0.1 inch in diameter and with a broad, flat head, was made of hardened steel. Two disks of steel were then prepared, through each of which a hole the size of the nail was drilled. A disk of marble 0.2 inch in diameter was then placed between the two steel disks and the nail was placed in the hole in the upper steel disk, so that it rested in a vertical position on the center of the marble plate. The whole was then placed in a copper tube and embedded in alum in the usual manner. Pressure was then applied and the whole was squeezed down. On dissolving away the alum the upper steel plate was found to have been distinctly bent by the moving alum, the head of the nail was broken into small pieces, but the shank of the nail had passed completely through the marble disk, making a clean, well-defined hole in the upper portion and shoving out a little conical-shaped piece of marble before it on the lower surface of the disk. The marble showed no trace of crack or fissure—the steel had passed directly through its substance. A photograph of the plate upon the completion of the experiment is shown in Plate VI, Fig. *a*, a new

nail of the same dimensions as the former one being inserted in the hole made by the latter.

B. LITHOGRAPHIC LIMESTONE: SOLENHOFEN, BAVARIA

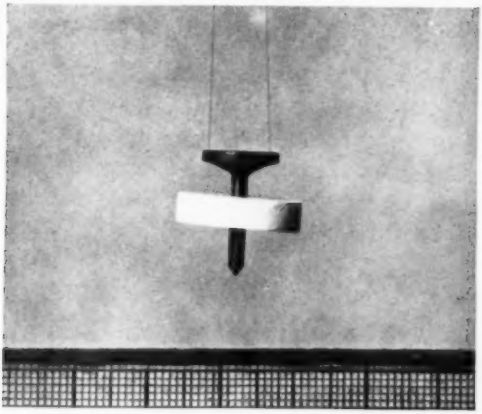
This is a buff-colored limestone of extremely fine and absolutely uniform grain, containing about $3\frac{1}{2}$ per cent of various impurities. It breaks into a splintery or conchoidal fracture. When a column of this rock is deformed in paraffine the result is similar to that obtained with Carrara marble, and in almost every case the same transverse cracks develop upon the removal of the embedding material.

In an experiment in which the rock was deformed in alum the column presented one of those highly interesting forms sometimes seen in deformed Carrara marble, dolomite, etc. This is produced by the development of a complete system of minute parallel faults crossing the column at an angle of 65° to the horizontal. The upper portion of the column thus tends to shear down along these planes, the rock however remaining hard and solid, indicating a deformation under conditions intermediate between those of the zone of fracture and the zone of flow, but more nearly approximating those of the latter.

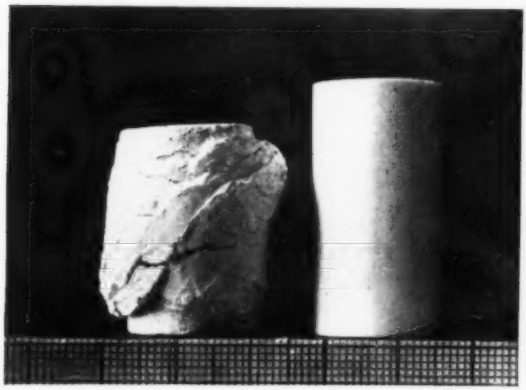
C. FOSSILIFEROUS LIMESTONE: BELGIUM

This is a dark-gray, highly fossiliferous limestone.

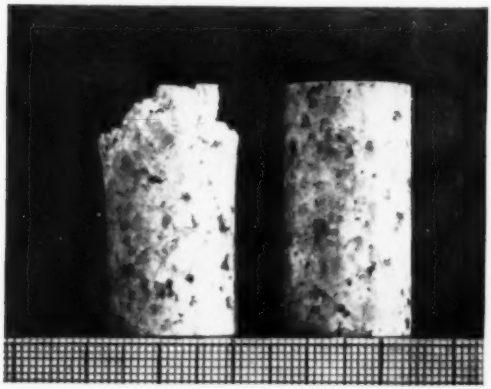
A column was embedded in alum and deformed in the usual manner. The height of the column was reduced from 1.574 inches to 1.4 inches, and the column yielded to pressure in such a manner that instead of bulging symmetrically it developed a movement exactly like that described in the experiment with Solenhofen limestone; that is to say, the upper portion of the column moved down over the lower portion at an angle of about 45°, the movement being concentrated along a strip about half an inch wide. In this strip there were several parallel planes in which the movement was especially pronounced, but within this zone the whole mass was seen to have been more or less plastic. Thin sections of the rock in this portion of the column when examined under the microscope showed little lines of minutely granulated material, often presenting a minutely brecciated structure, the whole constituting a species of "distributed fault." The rock after deformation was apparently as hard and solid as before.



(*a*) Steel tack forced through marble disk by differential pressure



(*b*) Dolomite—Cockeysville, Md.—before and after deformation



(*c*) Column of Baveno granite before and after compression

D. BLACK MARBLE: BELGIUM

This is the well-known ornamental stone which in commerce is known as "Belgian Black" or "Noir Fin." It is an impure, somewhat bituminous limestone, which is impalpably fine in grain, breaking with a splintery fracture like glass, and which takes a very high polish and is extensively used for interior decoration.

When thin sections are examined under the microscope the rock is found to be so fine in grain that a high power is necessary to resolve it. It is composed of minute calcite grains from 0.02 mm. to 0.002 mm. in diameter and of irregular shape, between and around which are occasional minute films and spots of a black color.

When submitted to compression in paraffine it gave rise to forms identical with those developed in the Solenhofen limestone under the same conditions.

When sulphur was employed as an embedding material, the ends of the column were found to have been forced into the central portion, with the consequent development on the exterior surface of a most complicated series of little tongues or wedge-shaped portions of the rock, sheared up one upon the other like overlapping shingles, thus giving rise to a corresponding increase in the thickness of the deformed column as its height is reduced. The rock after deformation remained hard and solid; it could be rapped sharply on a table without breaking. The cohesion may have been due in part to a little sulphur which had soaked into the column, acting as a cementing material. No trace of sulphur, however, could be detected on the surface of the column, the heat to which it was subjected after the sulphur had melted and drained away having entirely volatilized any portion of that substance that still remained adhering to the rock.

When alum was employed, the surface of the deformed column was found to be covered with a great number of sharp and more or less wedge-shaped pieces, often separated by minute open cracks, of which a great number traverse the column. The end faces of the column were also divided into separate areas, often separated by open cracks, which areas form the bases of wedges which have been faulted up or down. The resulting form is similar to that obtained when the rock is deformed in sulphur. The little wedges showed no evidence of plastic deformation. The rock was broken in a marvel-

ously complicated manner, but there no plastic flow was discernible. The rock under the conditions of the experiment acts essentially as a brittle body.

E. DOLOMITE: COCKEYSVILLE, MARYLAND

This is a typical dolomite, the analysis showing that the carbonates of lime and magnesia are present very nearly in their molecular proportions. It is white in color, practically free from impurities, perfectly crystalline, of medium grain, and is extensively employed as a building stone.

A column when deformed in paraffine wax in the usual manner was found upon the completion of the experiment to have assumed the same form as in the case of Carrara marble. The upper portion, where the deformation was greatest, showed very plainly two sets of lines crossing its surface and intersecting at angles of about 60°. The upper end of the column at a number of places was commencing to shear down in triangular-shaped masses. From the portion of the column where the deformation had been greatest a series of thin sections was prepared. When these were examined under the microscope the rock was seen to be traversed by many little branching lines of finely granulated material, which lines however intersected, giving a rude, diamond-shaped network. The individuals composing those portions of the rock between these lines were somewhat flattened in shape and showed distinct strain shadows.

The dolomite was then deformed in alum in the usual way, the load required being 33,000 lbs. The deformed column presented a striking appearance and showed in a most beautiful manner on its surface the leaflike forms due to movements along Luder's lines, described in the case of the Carrara marble, but the dolomite is seen to be somewhat less plastic than the Carrara marble, for in several places the column was torn by the movement in directions other than those followed by Luder's lines, this tearing giving rise to open and ragged rents in the substance of the column after the alum had been dissolved away. The form is very suggestive (Plate VI, Fig. *b*). The rock moved as an exceedingly stiff, semi-plastic mass. The upper portion of the column is commencing to shear off along a plane inclined at an angle of about 60° to the horizontal. The movement

however is, as has been mentioned, that of a stiff paste, not that of a brittle solid.

F. IMPURE MAGNESIAN LIMESTONE: HULL, CANADA

This is a very impure magnesian limestone, containing about 50 per cent of insoluble residue in the shape of minute subangular grains of clear quartz. The rock is of somewhat open grain and porous character and has been used very extensively for the production of hydraulic cement.

When deformed in paraffine, triangular portions of the column were found to have sheared off around the end, as in the case of other purer varieties already described. These remain adhered to the column, which also shows a marked tendency to develop cracks, crossing it at right angles to its length, i.e., at right angles to the direction of the pressure.

A column of the usual dimensions was then deformed in alum in the usual manner under a load of 31,000 lbs. On dissolving away the alum, however, the deformed column went to pieces, but from the shape of the fragments it could be seen that the movements developed in it had been of the nature of a complicated shearing similar to those already described.

G. BIOTITE GRANITE: BAVENO, ITALY

Columns of granite of the usual size and with a polished surface were embedded in alum inclosed in a copper tube in the usual manner and submitted to the pressure required to squeeze the whole down until the copper tube displayed signs of incipient rupture. The load required for this purpose was 50,000 lbs.

When the alum was removed by solution, the granite at one end of the column was found to have remained intact. Toward the middle, however, the column had undergone a distinct bulging due in part at least to a movement along little planes of thrust or shearing, although the work was still quite coherent, the movement in question having given rise to a rude gneissic or schistose structure owing to the arrangement of strings of mica and grains of orthoclase parallel to the base of the column. The other end of the column where the motion had been greatest was disintegrated by the movement and fell

to powder when the alum was dissolved away. A photograph of one of the columns as it appeared when freed from the alum is shown in Plate VI, Fig. *c*, but as in this particular case the movement was not so great as in others, the gneissic structure referred to is not well seen. When examined under the microscope, both quartz and orthoclase show well-marked strain shadows, but even a very careful examination under a high power between crossed Nicols fails to show with certainty whether the shadows in question are due to an actual bending of the mineral or to a fracture of the mineral with a slight shifting along an infinite number of ultra-miscroscopic cracks.

In several cases, however, where the conditions for observation were very favorable, no signs of such cracks could be detected and the mineral seemed to have undergone an actual twisting.

The biotite individuals had been very distinctly bent and twisted.

The rock displays a remarkably perfect cataclastic structure along certain lines or streaks where the quartz and orthoclase are represented by larger fragments, which, however, are mingled with those of smaller size, as well as with others which pass into almost ultra-microscopic dimensions.

SUMMARY

1. Under the differential pressures developed by this method of experimentation, that is by employing Kick's process, using fused alum or the other embedding materials employed, and tubes of copper with walls of from 0.125 to 0.25 inch (3.175 to 6.38 mm.) in thickness, minerals which have a hardness of 5 or under (Mohs's scale), show distinct plastic deformation, this deformation being less pronounced in the case of the harder minerals.

2. The minerals above 5 on the Scale of Hardness, while not presenting any marked change in shape, in some cases show evidences of internal movement. Thus a perfect basal twinning is developed in diopside, similar to that so often seen in specimens of this mineral from the crystalline limestones of the Grenville series.

3. In the case of very hard minerals, no evidence of plastic flow was discernible; their structure was broken down and they were reduced to powder.

4. Under the differential pressure fluorspar not only changed its form but also its color.

5. The softer rocks, such as Carrara marble, are readily deformed, the shapes assumed varying somewhat with the character of the material in which the rock is embedded during deformation. The movement takes place in part by distortion of the calcite grains and in part by the development of a cataclastic structure in the rock.

6. Crystalline dolomite is more resistant. The movement induced in it resembles that produced in a very stiff paste. This movement takes place chiefly through the development of cataclastic structure.

7. Very fine-grained massive limestones display a movement in which flowing and fracture are combined.

8. The harder rocks, like granite, crumble under the pressure, although in those places where the movement is very slight, the rocks develop an indistinct foliated structure owing to the granulation (cataclastic structure), with movements in the granulated portion of the rock.

9. For the development of a flow structure in the harder rocks, much higher differential pressures are required than are obtained by this process—such differential pressures, for instance, as may be secured when the rocks are inclosed in steel before being submitted to the deforming load.

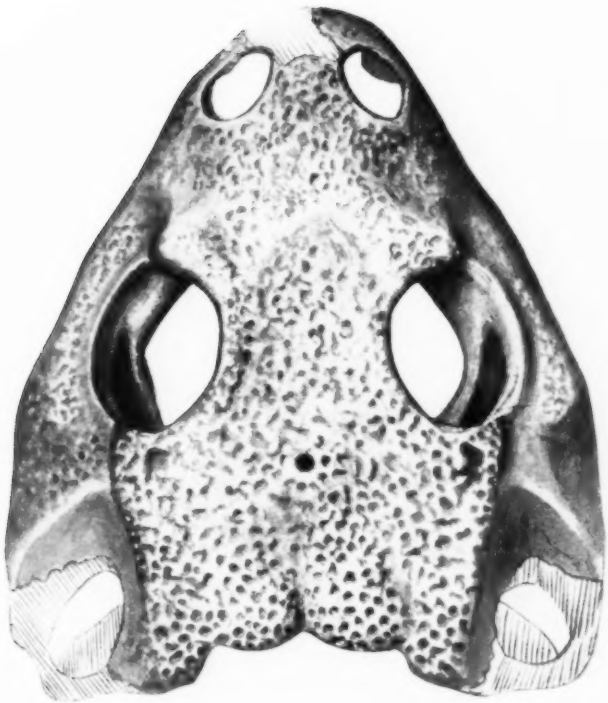
DISSOROPHUS COPE

S. W. WILLISTON
The University of Chicago

The material herein described and figured was collected by the writer from the upper or Clear Fork Division of the Texas Red-beds on Coffee Creek, in August, 1909. It comprises a nearly complete skull, but little distorted, the two scapulae with attached cleithra, neither complete, but the two supplementing each other nearly perfectly; the two complete clavicles attached to the incomplete interclavicle; the two humeri, one complete save for the capitellar angle, the other with the distal part quite complete and the proximal portion missing; two attached proximal carpals, several vertebrae and fragments of ribs, the nearly complete carapace, a broken and somewhat distorted pelvis, a femur, and fragments of epipodial bones.

For the most part, the surface of the skull is unimpaired, showing deep, almost circular pits, with narrow, reticulating ridges between them. The pittings seem to be most pronounced in the upper posterior part. There are no indications of mucous grooves, and I am convinced that, were they originally present, evidences of them would be apparent. Nor, as in the case of the skulls of *Cacops*, can I distinguish the sutures.

The skull is very broad posteriorly, with a rounded, obtuse muzzle. The orbits are situated about midway in its length; they are rather small, nearly circular in outline, and broadly separated. The table of the cranium, back of the orbits, is rather broader than long, a little wider anteriorly, with a broad emargination behind; it is nearly plane, with its margins elevated. The parietal foramen is situated a little back of a line drawn through the posterior margin of the orbits. Just back of each orbit there is a distinct depression, as in *Cacops*, apparently for the lodgment of some gland. In the middle part behind there is, on each side, a prominent, nearly hemispherical elevation, deeply impressed with large pits; they correspond to the prominent rugosities of the *Cacops* skull, but are much more rounded and less



angular. Behind, these swellings are partly separated by an angular emargination of the hind border. The epiotic region on each side is produced backward considerably beyond the transverse line of the rounded swellings. The broad surface between the orbits is shallowly concave transversely. The thickened upper margin of the orbits is nearly horizontal to the middle of the orbit in front, where there is a rugosity, the outer border of which is nearly vertical. The face in front of the orbits is convex, with a depression on each side in front of the orbital rugosity. The nares are large, oval in outline, and are directed upward and outward and forward. Below and a little behind the orbits there is a distinct elevation or rugosity. The posterior lateral or temporal region is unfortunately wanting on each side, or rather the parts were so mutilated that they could not be joined. The structure here is quite surely as in *Cacops*, the epiotic prolongation with its attached quadrate inclosing the ear opening at the bottom of a cavity. The upper margin of this opening is preserved in part on the left side, as is also most of the smooth bone forming the anterior part of the auditory cavity, the ridge limiting this surface from the roughened exterior of the side of the skull in front of it running downward and backward from a point about ten millimeters back of the orbital margin, to the jugal border.

On the palatal side of the skull the basioccipital, basisphenoid, and parasphenoid could not be recovered, nor the vomerine portion in front. On the left side the pterygoid and palatine regions are nearly perfect and undistorted, save for the interior border of the nares. The nareal opening is long and narrow, the anterior margin a little in advance of the posterior border of the external opening. In front the external border is very close to the dental margin; behind, it is removed a few millimeters. Near the posterior margin of the opening there is a single large tooth, as in *Cacops*, and doubtless there was another on the vomers at the anterior inner border; no other palatine or pterygoid teeth are visible. The infratemporal opening between the pterygoid and jugal margin is shorter and narrower than in *Cacops*, and the lateral process, doubtless corresponding to the transpalatine, is smaller. The basisphenoid process of the pterygoid is stout, transverse, and nearly horizontal. Evidently the structure throughout of the palatal surface was quite alike in the

two genera. Parts only of the walls of the rhinencephalic chamber are preserved.

The maxillary teeth, which extend backward to opposite the beginning of the infratemporal opening, are all very small, and are much more numerous than in *Cacops;* I count about forty-five in each maxilla. Those preserved entire are scarcely more than two millimeters in length.

The mandibles, which, with the exception of the extreme anterior end, are preserved complete, are, like those of *Cacops*, slender bones, deepest immediately in front of the cotylus, with a relatively high coronoid process, which fitted into the infratemporal fossa. I count about thirty-five teeth in each dentary, as preserved. The external surface, at least posteriorly, is closely impressed with circular or oval pits, like those of the cranial table.

Carapace.—The carapace, as preserved, is of essentially the same character as that of *Cacops*, but of a far greater development. In the series, as adjusted, there are indications of twelve or thirteen vertebrae participating in the shield, and others possibly are lost. The whole number may have been the same as in *Cacops aspidephorus*, that is, fifteen, but I suspect there were more. The first dermal shield, covering three or four vertebrae, appears not to have been intimately associated with the spines of the vertebrae. It is very large, not much broader than long, and heavy. Its front border is very obtusely angular in the middle with the borders receding and rounded. The lateral borders are subparallel and gently convex in outline. The posterior border has a gentle emargination in the middle with the lateral sides slightly convex behind. The planes of the sides have an angle of nearly forty-five degrees with each other and are broadly rounded in their union. The dorsal surface is rather deeply pitted, the depressions rounded or oval with reticulating ridges between them. The under surface is smooth, and appears not to have been underlaid with lateral expansions of the spines. Back of this shield, on the under side, there are nine spine dilatations, the first six or seven complete in the specimen. They are thin, flat plates, apparently co-ossified with the rather slender spines above, directed nearly transversely, with a less angle of declivity than has the nuchal or scapular shield. The outer extremities are narrowed or obtusely pointed, their upper

surface beveled both in front and behind for the dorsal shields. Their surface is smooth throughout.

The dorsal shields are rather stout, elongate bones, rounded on their outer extremities, pitted on their dorsal surface like the nuchal shield, forming a rather uniform arc of a circle, with less steepness on the sides than that of the nuchal shield. These shields, thick in their middle line, thinned along their anterior and posterior margins, leave a space of from two to four millimeters between their adjacent borders, in which the smooth surface of the spinal expansions is visible.

Vertebrae.—Not many of the vertebrae are preserved, and such as are, are not in the best condition. They do not seem to differ from the vertebrae of *Cacops* in any essential respect. The vertebra connected with the first dorsal spinous expansion has the proximal end of the ribs attached. It is broad and flat, articulating with the transverse process and hypocentrum like the early ribs of *Cacops*. The ribs evidently had no uncinate projections like those of *Aspidosaurus* or *Euchirosaurus*. The under surface of the more posterior expansions is shown characteristically in Broili's figure (*Paleontographica*, LI, Pl. V, Fig. 5*b*).

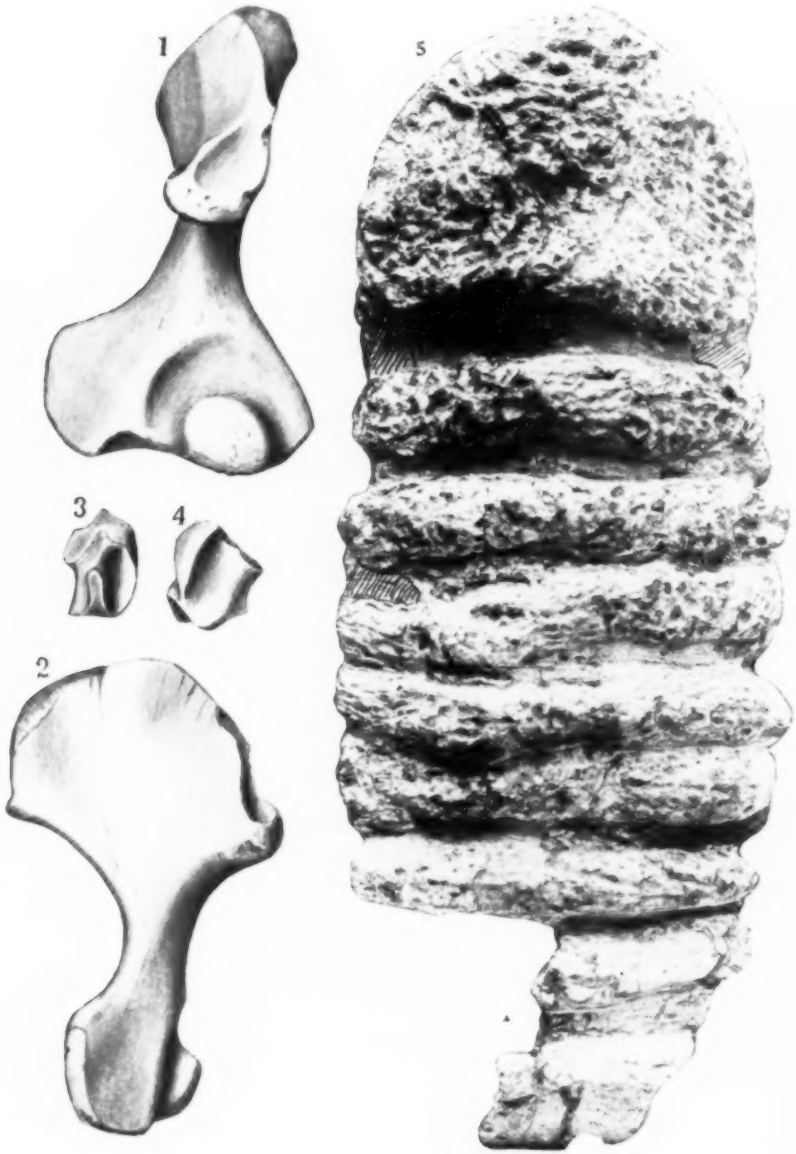
Scapula.—The scapula of *Dissorophus* differs markedly from that of *Cacops* in its greater robustness and in its more upright position. The posterior border is thickened and has a more pronounced convexity near its middle. The preglenoid facet is very prominent as a sharp ridge, immediately below which is the opening of the infraglenoid or supracoracoid canal and, close by, back of the lower part of the same facet, is the opening of the glenoid canal. The ridge continuous with the preglenoid facet is less prominent than in *Cacops;* the post-glenoid part, or metacoracoid, is more extensive, the concavity between it and the hind border of the shaft is deeper. On the inner side the deep fossa into which opens the supraglenoid and infraglenoid canals is deeper and shorter, and the epicoracoid portion is much broader below and internally to this fossa. The opening for the glenoid canal on the inner side, as in *Cacops* and *Trematops*, is opposite the lower part of the fossa.

The three glenoid foramina or canals, which I have called the supraglenoid, glenoid, and infra glenoid, appear to be characteristic of the rhachitomous amphibians, if not of the temnospondyles. I have

no knowledge of the occurrence of all three in other vertebrates. In *Labidosaurus* the scapula-coracoid, which has a wonderful resemblance to these forms, has a distinct supraglenoid opening in the same position, opening internally in the same way with the inner opening of the infraglenoid foramen in a smaller fossa. So, also, in the pelycosaurs there is a corresponding foramen, though it may pierce the bone more in advance of the glenoid depression. In none of these forms, however, have I been able to distinguish a glenoid foramen; certainly there is no inner opening corresponding to that of the amphibians in any of these reptiles. In *Varanosaurus* the sutural line between the scapula and coracoid (epicoracoid or procoracoid) passes backward through the preglenoid facet, and through the place where the glenoid foramen should be, were there one. The suture for the metacoracoid (coracoid auct.) is back of this place in *Varanosaurus*. Unfortunately, in none of the amphibians have I, or others, been able to distinguish the divisional sutures between scapula and coracoid in front, or that between the scapula and coracoid and the metacoracoid behind. There can be scarcely a doubt that the extraordinary resemblance of the amphibian girdle to that of the cotylosaurs and pelycosaurs extends also to its intimate structure, and that the relations between the scapula, coracoid, and metacoracoid are identical in the two groups. The demonstration of this, however, is not yet possible. What the significance of the glenoid and supraglenoid canals is in the amphibians, the supraglenoid in the reptiles, must await further researches. The latter is present in *Iguara*.

The cleithrum or supraclavicle is a much heavier, but more slender bone in *Dissorophus* than in *Cacops*. It lies, as in that genus, loosely over the top of the scapula, not suturally united with it, arching roof-like over the top. In front it descends over the rounded superior anterior angle of the scapula, fitting into a depression of that bone. Below, it unites by a long oblique suture with the upper end of the clavicle, extending as a narrow, anteriorly curved process quite to the place where the coracoid turns inward, that is doubtless to the sutural line between scapula and coracoid.

Various views have been entertained as to the origin, nature, and fate of this bone; the one usually accepted is that of Gegenbaur, that it represents a like bone in *Polypterus;* and this seems to be altogether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probable. As to its fate, the only theory suggested is that of Gaudry, that it represents the acromial ossification of the higher vertebrates; and this too seems not unreasonable. The union between clavicle and cleithrum in *Dissorophus* is a very close, sutural one; in the early reptiles only the lower end of the cleithrum is left; the co-ossification of this with the scapula would account for the acromion, if it be not a mere epiphysial ossification. In *Eryops* the cleithrum is suturally united throughout with the scapula above, in the position of the supra-scapula.

Interclavicle.—The interclavicle is a broad, gently concave, and thin bone, resembling that of *Cacops*, but larger and broader. It has a rounded, thin border anteriorly, and similarly rounded, thin lateral margins. Posteriorly the bone is broken away but the thickened median part indicates a posterior median extension, probably as in *Cacops*.

Clavicles.—The clavicles are large, broad, smooth bones, meeting each other in the middle line, and covering, for the most part, the interclavicle. They are convex below, with their greatest expansion some distance away from the middle. In the position in which the girdle now is, evidently the normal one, the cleithral ends are directed vertically upward, nearly parallel to each other, with an interval of a little more than two and a half inches between their upper extremities, which are suturally and closely united to the lower ends of the cleithra or supraclavicles. The upper extremity is much stouter and broader than is the case with *Cacops*.

Upon the whole, the pectoral girdle, both primary and secondary, is remarkable for its stoutness and firm articulations.

Humerus.—Of the two humeri, the left is preserved completely save the capitellar angle, while the right has the lower end perfect with the upper extremity wanting. In the figures the capitellar portion has been reversed from the right side. In general shape and structure the bone resembles that of *Cacops* closely, so closely that there may be difficulty in distinguishing them in ill-preserved specimens. The humerus of *Dissorophus* is distinctly stouter, with the ends a little more expanded and the lateral curvatures a little deeper; the entepicondylar expansion is stouter.

Femur.—The right femur is preserved in pretty good condition

save the external condyle and a part of the lower portion of the crest. Its resemblance to the femur of *Cacops* is close, but, like the humerus, differs in its greater stoutness. The adductor crest is heavier, and not as deep, the shaft is distinctly stouter. The articular surface for the tibia is rather better defined than in any of the specimens of *Cacops* examined. The surface is flattened, or with a gentle antero-posterior convexity with sharp rims. It is broadest on the inner side, narrower in the middle, and again somewhat expanded from before back on the outer side. The surface looks backward at an angle of about forty-five degrees from the longitudinal plane of the bone, with a light obliquity inward.

A large part of the left innominate bone is preserved, enough to demonstrate its close resemblance to the corresponding element of *Cacops*. Nor do the proximal ends of the tibia and ulna differ materially; like all the other parts, they are stouter.

The relationships between *Dissorophus* and *Cacops* are very evident, so evident, indeed, that for some time I was in doubt of their generic distinction. It would seem, however, that the much greater development of the carapace in *Dissorophus* together with the presence of the very large shield, which seems to be entirely absent in *Cacops*, together with other differences in skull and pectoral girdle, is amply sufficient to separate the two forms generically. And it is also evident that these two genera, presenting the unique characters they do, are entitled to a higher rank than genera. The characters of the family Dissorophidae I have already given, as based upon *Cacops* and *Dissorophus*. Whether or not the genus *Aspidosaurus* Broili should be placed in the same family is a matter of doubt. So far as the carapace is concerned the differences seem radical, in the absence of spinous expansions of *Aspidosaurus*, the dermal shields forming a shingle-like imbrication. However, other characters, so far as the known details furnished by the type specimen of *Aspidosaurus* are concerned, seem very like those of this family, and it is possible that the family characters may have to be emended in the future to include Broili's genus.

Although the known remains of *Zatrachys* are yet very meager, it would seem certain that the genus cannot be included with *Dissorophus*, and that the family Zatrachydidae will find eventual justi-

fication. The remarkable characters of *Trematops* also justify the creation of a family for its reception, with possibly *Acheloma* as an allied genus. Of the other American genera of temnospondyles, *Eryops* has long been considered of family rank, as also *Trimerorhachis*. None of these genera, so far as my knowledge goes, possessed either dermal or ventral armature, other than the carapacial development of the Dissorophidae and Zatrachydidae. Dermal plates have been accredited to *Trimerorhachis*, but I believe wrongly, since several specimens in the Chicago collection although including almost all parts of the skeleton give not the slightest indication of such. Nor were there any dermal plates, ventral or dorsal, in either *Trematops* or *Eryops*, and I am convinced that none will be found in *Zatrachys*, when better known. That there were amphibians in the American Permian with isolated dermal scutes is, I believe, certain from the evidence furnished by the Orlando bone bed, though perhaps they were all small animals. Thevenin has discovered dermal ossifications in *Euchirosaurus*, which he believes to be identical with *Actinodon*, and, furthermore, from his figure and descriptions of the ribs in that genus, it is quite certain that its relationship with *Eryops* is not nearly so close as has been thought, and as Thevenin believes. Similarly expanded ribs are characteristic of *Aspidosaurus*, apparently. Furthermore, we have no evidence so far, among the American forms, of a long tail, unless it be in *Trimerorhachis*, which differs so much in many ways from the other temnospondyles that it may well be it had also a long tail. Thevenin gives the number of presacral vertebrae in *Euchirosaurus* as twenty-two or twenty-three, I have determined the same numbers in *Trematops*, while in *Cacops* the number is positively fixed at twenty-one. Branson[1] gives the number for *Eryops* as twenty-five or twenty-six, though he found in no specimen more than twenty-four in a continuous series. Perhaps there is some variation in the various genera, but evidently the number never greatly exceeded twenty-two. Branson speaks of a small isolated arch in the atlas; if he be correct, the atlas differs materially from those of *Trematops*, *Cacops*, and *Dissorophus*. But I believe it will be found that the *Eryops* atlas was of like structure, that is, with co-ossified neuro- and hypocentra, with the sides of two neurocentra separated above. Bran-

[1] *Journal of Geology*, VIII, 605.

son described all the presacral vertebrae of *Eryops* as having double-headed ribs, attached to diapophysis and hypocentrum, while in *Cacops* it is only the anterior vertebrae which articulate with the hypocentrum and this is also clearly the condition in *Dissorophus*.

So far these are all the described genera of rhachitomous amphibia from the American Permian. The genus *Cricotillus* Case I suspect is identical with *Crossotelos* Case, a "Microsaurian" amphibian, while *Cricotus* is an embolomerous form.

Recently Case has discovered that *Otocoelus* is identical with *Dissorophus*, as indeed the figures given by Cope indicated. Whether or not the genus *Conodectes* Cope is also a related temnospondyl it is impossible to determine without examination of the type. The description given by the author of the genus is utterly inadequate for its recognition.

Following is a taxonomic summary of the known American Permian Amphibia.

CAUDATA.
- Lysorophidae Williston, 1909 (Paterosauridae Broili, 1904).
  - Lysorophus Cope, 1877.
    - tricarinatus Cope, 1877, Illinois, Texas, Oklahoma.

"MICROSAURIA" (Diplocaulia Moodie).
- Diplocaulidae Cope, 1881.
  - Diplocaulus Cope, 1877.
    - salamandroides Cope, 1877, Illinois.
    - magnicornis Cope, 1882, Texas.
    - limbatus Cope, 1896, Texas.
    - Copei Broili, 1904, Texas.
    - pusillus Broili, 1904, Texas.
- Crossotelidae Williston, 1909.
  - Crossotelos Case, 1903, Oklahoma.
    - annulatus Case, 1903.
  - ? Cricotillus Case, 1903, Oklahoma.
    - brachydens Case, 1903.

TEMNOSPONDYLI.
- Embolomeri.
  - Cricotidae Cope, 1884.
    - Cricotus Cope, 1873.
      - heteroclitus Cope, 1875, Illinois, Kansas.
      - gibsoni Cope, 1877, Illinois.
      - crassidiscus Cope, 1884, Texas.
      - hypantricus Cope, 1884, Texas.

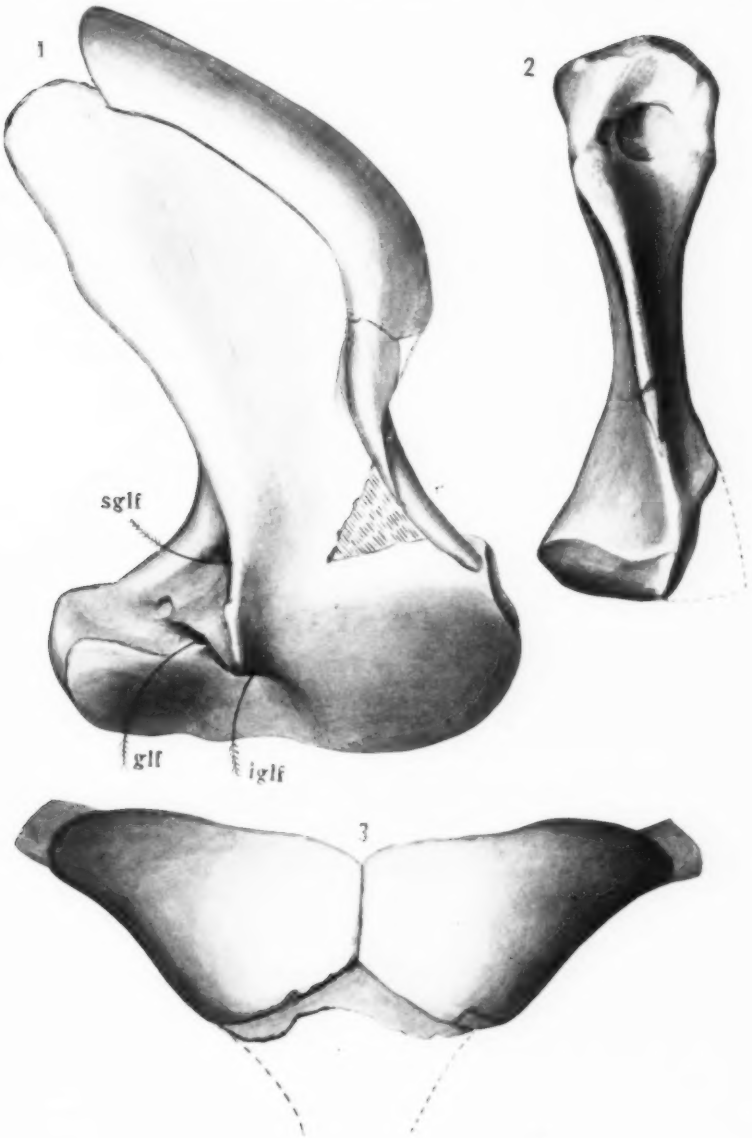
Rhachitomi.
- Eryopidae Cope, 1882.
  - Eryops Cope, 1877.
    - megacephalus Cope, 1877, Texas.
    - erythroliticus Cope, 1878, Texas.
    - ferricolus Cope, 1878, Texas.
    - reticulatus Cope, 1881, New Mexico.
    - latus Case, 1903, Texas.
  - Anisodexis Cope, 1882.
    - imbricarius Cope, 1882, Texas.
- Zatrachydidae, Nov.
  - Zatrachys Cope, 1878.
    - serratus Cope, 1878, Texas.
    - apicalis Cope, 1881, New Mexico.
    - conchigerus Cope, 1896, Texas.
    - microphthalmus Cope, 1896, Texas.
- Trematopsidae Williston, 1910.
  - Trematops Williston, 1909.
    - milleri Williston, 1909, Texas.
  - ? Acheloma Cope, 1882.
    - cumminsi Cope, 1882, Texas.
- Dissorophidae Williston, 1910. (Otocoelidae Cope.)
  - Dissorophus Cope, 1895.
    - multicinctus Cope (? articulatus Cope), Texas.
  - Cacops Williston, 1910.
    - aspidephorus Williston, 1910, Texas.
  - ? Aspidosaurus Broili, 1904.
    - chiton Broili, 1904, Texas.
- Trimerorhachidae Cope, 1891.
  - Trimerorhachis Cope, 1878.
    - insignis Cope, 1878, Texas.
    - bilobatus Cope, 1883, Texas.
    - conangulus Cope, 1896, Texas.
    - mesops Cope, 1896, Texas.
    - leptorhynchus Case, 1903, Oklahoma.
- Incertae sedis.
  - Cardiacephalus Broili, 1904.
    - sternbergi Broili, 1904, Texas.

EXPLANATION OF PLATES

PLATE I.—*Dissorophus multicinctus* Cope; dorsal view of skull. Three-fourths natural size.

PLATE II.—*Dissorophus multicinctus* Cope. 1, left humerus from in front; 2, the same from inner side; 3, 4, proximal carpal bones; 5, dorsal view of carapace. All figures natural size.

PLATE III.—*Dissorophus multicinctus* Cope. 1, right scapula-coracoid, with attached cleithrum, from outer side; 2, right femur, from behind; 3, clavicular arch, from below. All figures natural size.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A MOUNTED SKELETON OF PLATECARPUS

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In the summer of 1903, Professor E. B. Branson, then a student of the University of Chicago, discovered, near the mouth of Hell Creek in Logan County, Kansas, and collected with my aid, a remarkably complete specimen of a species of *Platecarpus*, which I refer, with little hesitation, to *P.* (*Holosaurus*) *abruptus* Marsh. In its vicinity another specimen almost identical with it in size and characters was discovered by Mr. E. Ball of the same party. A brief reference to some of the characters of the more complete of these two specimens was given by me in this *Journal* for January, 1904 (p. 30), and, later, Mr. S. R. Capps, under my advice, made a careful study of the hind extremity, publishing his results in this *Journal* for May, 1907 (p. 350). Since then both of these specimens have been thoroughly worked out of the matrix by Mr. Paul Miller, and one of them has been mounted as a wall specimen in the Walker Museum of the University of Chicago, a photograph of which is given in the present communication. It was first planned to mount the more perfect of the two specimens, but the horizontal flattening of the skull rendered it less adaptable for a plaque mount, and the specimen has been reserved for a free skeletal mount at some later time. The less complete of the two has therefore been placed upon the wall, its missing parts reproduced by casts from the more perfect one; this specimen fortunately had its skull bones preserved separately, in a macerated condition, with but little or no distortion, permitting their articulation in a normal position. The vertebral column was very complete and continuous to about the seventieth vertebra, that is the forty-seventh of the tail. The pectoral girdle, save the right humerus, and most of the hind paddles and pelvic girdle were preserved, in large part, in their natural relations; of the ribs many of the shorter ones were gone; these, together with the distal portion of the tail, have been reproduced from the other specimen, and the left humerus has been used instead

of the right. The specimen, therefore, has very little that is conjectural about it save the terminal phalanges of the paddles. Of the more complete specimen the vertebral column lay with every vertebra articulated and in position from the skull almost to the extreme tip of the tail, the last one preserved measuring about eight millimeters in diameter. Of the many hundreds of specimens of mosasaurs which I have collected, I have seen but very few with the extreme tip of the tail preserved in position; the small nodular terminal centra, feebly attached in life, are almost always dispersed. Of this series of vertebrae seven are cervical, twenty-three are dorsal, the first non-costiferous vertebra being the twenty-fourth. This is one more than I have found positively in other specimens, and in the specimen mounted, and is precisely the number I found in specimens of *Tylosaurus proriger;* while Osborn has recorded twenty-two as the number found by him in a specimen of *Tylosaurus dyspelor.* Of the caudals, six are pygals, one more than I have found in specimens of *Platecarpus coryphaeus.* Seventy caudal vertebrae were preserved in position, to which perhaps six or eight terminal nodular ones may be added, making eighty-five or eighty-six in all, about the number estimated by me as characteristic of *Platecarpus.* The distal caudals have, it is seen, a distinct elevation of the spines, a character I have never seen in other specimens of *Platecarpus.* Osborn has figured the tail of *Tylosaurus dyspelor,*[1] with a distinct elevation of the distal spines. His figures and statements do not need corroboration; the character certainly exists in the figured specimen. On the other hand, v. Huene[2] has recently figured specimens which he refers to the same species, which do not

[1] *Memoirs American Museum,* I, Pt. IV, 178.

[2] *Geologische paleont. Abhandlungen* (1910), VIII, 297.

show this distal expansion of the tail, and which the author denies. He also finds in the tail positive evidence of ninety-six caudal vertebrae (including the pygals), and estimates, though I think on insufficient foundation, twelve or fourteen more. (I may say, parenthetically, that the position in which bones are found in the Kansas chalk has no value as an indication of missing parts.) In the species *T. proriger* I have found eighty-eight as the full number in a specimen, in which every vertebra was found articulated, from the skull, to the minute ones of the tail. This specimen I have recently re-examined in the University of Kansas. There may have been one or two vestigial nodules at the extreme tip missing. In this specimen there was no conjecture, each vertebra as it was taken from its articulated position was numbered, and placed in its original position in the mounted specimen. From all of which facts it would seem to be evident that there may be individual or specific differences as regards the number of vertebrae in the mosasaurs.

In comparison of the paddles as shown in this restoration and as figured by Capps (*op. cit.*) it will be seen that the numbers of phalanges do not quite agree. A further examination of the various paddles of this genus leads me to the conclusion that the supposed missing phalanges in the specimen figured by Capps were not real, and that practically all the phalanges were secured. I think that the numbers for the different toes were essentially those originally given by Marsh for *Platecarpus* (*Lestosaurus*).

Here too, as is conclusively shown by a comparison of the paddles of the American Museum specimen of *Tylosaurus dyspelor* with that of *Tylosaurus proriger* of the University of Kansas, there are either individual or specific differences.

Huene finds in one of his specimens of *T. dyspelor* what he believes to be vestigial nasal bones. I quite agree with him that the nasal bones in the mosasaurs are not fused with the extremity of the premaxillae, but I have never found in any of the numerous specimens of mosasaurs any vestigial bones that seem beyond doubt to be the real nasals, such as Huene figures. I have seen in several skulls remains of the suture between the post-orbitals and post-frontals, but almost invariably the suture is wholly obliterated, and it may be possible that the nasal bones are thus indistinguishably fused in most specimens of

Platecarpus. Quite certain it is that in the specimens under consideration there are no such separate bones. Incidentally I may mention that in *Pteranodon* among pterodactyls the fibula is supposed to be absolutely wanting, yet in a specimen in our collection I find distinct remains of it fused with the tibia.

I have for some time agreed with Thyng and v. Huene in their conclusion that the real squamosal bone of the mosasaurs (and lizards) is that connecting the post-orbital with the so-called supratemporal bone, though Thyng, not reading my text but examining my figure alone, goes to considerable trouble to prove that I was wrong (see *Biological Bulletin*, VII, 189 ff.). But I agree with neither of these authors in considering the posterior element, that intercalated between the squamosal and exoccipital and pro-otic, as the so-called supratemporal. It is a matter of surprise to me how persistently all students of the temporal arch of the mosasaurs and lizards have ignored the description and figures of this bone given by Cope and myself. From Baur to the present time, save Merriam and myself, no one has paid any heed to Cope's descriptions. At the risk of being discursive I will quote what I have previously published in the article already quoted:

> Baur vigorously urged that the bone at the end of the suspensorium is the squamosal, but Baur never fully understood the relations of this bone in the mosasaurs, as is evidenced by his faulty description of it.[1] As Cope has repeatedly affirmed and as I have confirmed,[2] this so-called squamosal (supratemporal Huene) of the mosasaurs is intercalated between the exoccipital and the pro-otic, extending far inward, nearly to the surface of the braincase. It needs but a moment's consideration by any one familiar with the relations of this bone in these animals and in the mammals to be convinced that such remarkably different conditions cannot be those of the same bone. The inner part of the (squamosal) [deeply wedged in as it is between two cartilage bones] corresponds quite well with the outer part of the opisthotic, which was not found in the lizard embryo by Parker. "In some of the genera of Stegocephala the paroccipital is free from the exoccipital; in others (*Mastodonsaurus*) it is co-ossified with the exoccipital. The paroccipital is in relation to a dermal plate which is very improperly called the epiotic. I propose the name paroccipital plate for it."[3]

[1] *Journal of Morphology* (1892), VII, 14.

[2] Cope, *Trans. Amer. Phil. Soc.* (1892), XVII, 19; Williston, *Univ. Geol. Survey* (1898), IV, 121.

[3] Baur, *Journal of Morphology* (1889), III, 469.

It may be objected that the presence of an epiotic bone in the lizards is a far too primitive character, but we are now quite certain that the lizards are an extremely old group, probably dating from the Permian, and that they have not a few primitive characters, etc.

In a recent paper[1] I have again expressed the opinion that the squamosal of Baur, the supratemporal of Thyng, v. Huene, and others, is in reality the "epiotic," paroccipital plate, intercalare, tabulare, or post-temporal (for these are some of the names the bone has received) of the stegocephs.

In his discussion of the elements of the mandible I do not think that v. Huene does Baur justice. Baur it was who, for the first time, correctly made out the structure of the reptilian mandible. His mistake was in starting with the turtles as the basis of his revised nomenclature, instead of the crocodile, to which the names of the bones were originally given. This fact I tried to make clear in *Science*, and in my paper on the plesiosaurs,[2] where I introduced, for Baur's angular, the name prearticular, now generally used. Kingsley, later, overlooking this term (very naturally, for it was hidden away), reached the same conclusion, but gave the name dermarticular for the element in question, a term in some respects more appropriate than mine, but, because of doubtful homologies, not to be unreservedly recommended. The prearticular occurs as an independent bone in many, if not all dinosaurs, the chelonia, plesiosaurs, pelycosaurs, and probably all the old reptiles and stegocephs.

[1] *American Journal of Anatomy*, X, 82.

[2] *Field Columbian Museum Publications*, No. 73, p. 30.

OLDER DRIFTS IN THE ST. CROIX REGION[1]

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Some of the glacial features of the St. Croix–Dalles quadrangle were described in a previous number of this *Journal*.[2] That paper was based upon field studies during the summer of 1904. Up to that time no certain evidence of any drift-sheet older than the Wisconsin stage of glaciation had been recognized, and in consequence that paper confined itself to a discussion of the two drifts of Wisconisn age which occur as surface formations within the quadrangle. But with the aid of a class of students from the University of Chicago, during the field season of 1905, the presence of a considerable amount of drift distinctly older than the Wisconsin red drift was clearly recognized at a number of points along the St. Croix River. Two years later a study of the deep ravines which dissect the river bluffs opposite Osceola, Wis., resulted in finding that there are two very distinct drift-sheets in this region belonging to earlier glacial epochs. The earlier of these is a sheet of grayish-black drift brought in from the northwest by a Keewatin glacier. At some later date a sheet of pinkish-red or reddish-brown drift was spread over the region by a glacier from the Labrador center coming by way of Lake Superior.

THE GRAYISH-BLACK DRIFT

The deep ravines opposite Osceola which head back from the river to the Minnesota uplands afford the best opportunities to study the buried Pleistocene deposits of the region. At the bottom of the big ravine in the south part of Section 16, Franconia (about 100 yards east of the wagon road), is a gully-bank exposing ten feet of very dark grayish to bluish-black till. This dark drift is highly calcareous and contains relatively few pebbles and these mostly small. It is largely a rock flour derived by glacial grinding from limestone and

[1] Published by permission of the Director of the U.S. Geological Survey.

[2] R. T. Chamberlin, "The Glacial Features of the St. Croix–Dalles Region," *Jour. of Geol.*, XIII (1905), 238–56.

shale formations. The most common pebbles found in it are limestones, granites, and greenstones. In its upper portion it gradually becomes brown, passing into yellow-buff above. These brown and buff portions are obviously merely the partially oxidized phases of the drift which was originally nearly black in color. Upward the till becomes less and less calcareous, due to leaching. The great amount of calcareous and argillaceous material as well as the distinctive assemblage of crystalline pebbles in this drift indicates that the ice which deposited it came from the northwest and traversed the extensive limestone and shale areas of Manitoba. It is an unmistakable Keewatin drift.

So far as could be determined, it appeared to be identical with that great mass of bluish-black drift which makes up the bulk of the strong moraine ridge through which the Northwestern Railroad has cut its way, half a mile east of Hersey, Wis. This smooth ridge of thickened drift near Hersey marks an eastern border of a great Keewatin ice-sheet. Hersey is thirty-five miles southeast of the St. Croix River at Osceola, and hence Osceola should be almost in the line traveled by the Keewatin glacier which dumped Manitoban material near Hersey. The age of this grayish-black drift has not yet been conclusively established, but from what is known about it at the present time and the relations elsewhere in Wisconsin, Minnesota, and Iowa, it would seem best to assign it tentatively to the Kansan. Whether a pre-Kansan drift of similar Keewatin character and blackish color underlies it, as it does in some parts of Minnesota and Iowa, cannot yet be told.

The partially oxidized upper portion of this drift-sheet has been recognized in various portions of the St. Croix–Dalles quadrangle. The wagon road which leads from the Osceola bridge to the Minnesota upland country exposes in descending order the following section of older drift near the top of the river bank:

	Feet
1. Wash material including much from the Wisconsin drift	4
2. Gray-brown to yellow-brown calcareous till which breaks up into hard chunks	11
3. Stratified sand, light-colored above and rusty-brown below	3½
4. Dark-gray or bluish-gray till which is non-calcareous, apparently having been leached	2
5. Jordan sandstone.	

Above this section is a long slope with a rise of 35 feet to the highest river terrace. This old drift may therefore once have been fairly thickly covered with Wisconsin drift, since removed by the river.

One hundred pebbles averaging an inch in diameter were dug from the brown calcareous till (No. 2), and classified with the following result:

Fine-grained greenstones	29
Limestone	21
Granite (10 pink, 8 gray)	18
Gabbro-diorite	6
Quartz	4
Greenstone schist	3
Quartzite	3
Quartzose	3
Brown sandstone	3
Syenite	2
Mica schist	2
Red Lake Superior sandstone	2
Chert	2
Monzonite	1
Red porphyry	1
	100

The greenstones were largely of the dark Keewatin types. There seemed to be very little even among the gabbro-diorite group to suggest the Keweenawan lavas of the Lake Superior Basin. The glacier which deposited this drift received but little material from Lake Superior or from earlier Labradorean drifts.

Three miles east of Dresser Junction (T. 33 N., R. 18 W., Sec. 11, S.W. corner) the wagon road descending into a deep valley exposes a buff clayey till streaked through and through with silver-gray and bluish-gray portions like the typical banks of Kansan drift in Iowa. The calcareous material has been leached out of this oxidized portion of the till. The unaltered black drift was not seen. Fifty pebbles from this till were classified as follows:

		Percentage
Granite	12	24
Quartz	10	20
Fine-grained greenstones	8	16
Chert	5	10
Feldspar crystals	5	10
Syenite	3	6
Gabbro-diorite	3	6
Quartzite	2	4
Clay ironstone	1	2
Decayed igneous	1	2
	50	100

Pebbles in this exposure of the drift were small and scarce. They were mostly soft, showing evidence of much weathering and age. The classification of the pebbles collected shows the unmistakable Keewatin character of the drift even in the absence of limestone. The abundance of chert suggests the former presence of the calcareous element. This occurrence of western drift is three miles east of the limiting terminal moraine of the Keewatin glacier of the Wisconsin epoch, showing that this earlier Keewatin ice-advance was more powerful than the last.

The upper oxidized portion of this old Keewatin drift has now been recognized in limited sections in various other portions of the quadrangle. It has been brought to light in constructing the new railway spur from St. Croix Falls station down to the electric-power dam, and evidences of it have been seen on the Taylor's Falls side of the river. These occurrences suggest that if the entire region had not been buried beneath such heavy deposits of Wisconsin drift this supposed Kansan drift would be found to constitute an important sheet.

THE LOWER RED DRIFT

In the gully in which the true grayish-black till was first detected no pre-Wisconsin red drift was exposed to view, but in the next ravine to the north there was visible an intensely red, firmly consolidated till, or hardpan, upon which rested a rather ferruginous sand, and above that the fresher-appearing sand and gravel of Wisconsin age. A much better section is afforded by the wide, open ravine in the N.W. $\frac{1}{4}$, Section 15, Franconia ($1\frac{1}{2}$ miles southeast of Franconia). Near the head of this ravine the gray Keewatin drift of Wisconsin age is seen resting upon the red Wisconsin sands and gravels from Lake Superior and Labrador. Lower down toward the river is a bank of reddish-brown to pinkish-red sandy till which is bright carmine red at the top. Though a true red drift, it contains many limestone pebbles in some places and locally boils up briskly with acid. The Wisconsin red drift of this region is indifferent to acid and it is very seldom that a fragment of limestone is found within it. A sharply defined contact separates the hard red calcareous till from the overlying unconsolidated sands which undoubtedly belong to the Wisconsin red drift. At the top of the underlying red

till which becomes somewhat clayey at its upper surface, the writer found in 1907 small lumps of decayed vegetable matter and the remains of several tiny twigs. These were all in the uppermost inch of the red till. While there was no continuous layer of humus, these lumps and fragments of former branches were a decided feature of the contact. As this sort of material was found nowhere else in the red till or the sand above, it would seem to mark a true interglacial horizon. From the descriptions it appears to correspond closely with the humus horizon reported by Dr. Atwood and his class in 1904,[1] but which the writer has repeatedly sought but never been able to find, a fact due no doubt to later concealment.

Fifty pebbles from a calcareous portion of the lower red till were classified as follows:

		Percentage
Limestone	14	28
Fine-grained greenstones	9	18
Red Lake Superior sandstone	9	18
Granite (1 pink, 3 gray)	4	8
Red aphanitic	3	6
Jasper	2	4
Quartz	2	4
Chert	2	4
Quartzite	2	4
Red quartz porphyry	1	2
Gabbro-diorite	1	2
Mica schist	1	2
	50	100

The red rocks and the character of the greenstones show that this is clearly a Lake Superior drift, but the presence of so much limestone is surprising. Perhaps the ledges which furnished the limestone were covered by drift at the time of the Wisconsin ice-advance, so that the glacier failed to gather up much of this material. There does not seem to be very much black drift below the red at this point, since the rock appears quickly as one goes down the ravine.

Several of the cuts along the Northern Pacific Railroad, between Taylor's Falls and Franconia, show glacial deposits older than the Wisconsin red drift. A cut in the middle of the east line, Section 35, Shafer, exposes a rusty-looking gravelly deposit resting upon the Franconia sandstone. Though much obscured by talus, this deposit was seen to have a thickness of at least twenty feet. The upper part

[1] See *Jour. of Geol.*, XIII, 248.

of the cut is a bank of red Wisconsin drift. Fifty pebbles from this gravelly deposit under the Wisconsin drift, taken from a point six feet above the Franconia sandstone, were classified as follows:

		Percentage
Fine-grained greenstones	14	28
Red Lake Superior sandstone	7	14
Red quartz porphyry	4	8
Jasper	4	8
Brown sandstone	4	8
Granite	4	8
Gabbro-diorite	3	6
Quartz	3	6
Red diorite	2	4
Red aphanitic	2	4
Quartzite	2	4
Decayed igneous	1	2
	50	100

This is clearly a Lake Superior drift brought in by an ice-advance from the Labrador gathering-ground.

This lower red-brown drift is older than the Wisconsin red drift and younger than the grayish-black drift of supposed Kansan age. The nature of its occurrence within the St. Croix–Dalles quadrangle does not afford any very tangible clue to the age of this deposit. But it appears to be almost identical in lithological characteristics, degree of induration, and various minor peculiarities with the sheet of pre-Wisconsin red drift which forms the prominent moraine near the village of Hampton in central Dodge County, Minn. This is fifty miles S.S.W. of Osceola. In this moraine the hummocks still persist, though they have been much sharpened by slope-wash and are now peaked or conical in shape. From the amount of erosion and general appearance of this drift it seems perhaps best to assign it for the present to the Illinoian glacier from the Labrador center.

Similar pre-Wisconsin red drift overlies the grayish-black till in many cuts along the line of the Northwestern Railroad between Hersey and Baldwin, Wis. Some of these exposures show that a considerable interval of time elapsed between the retreat of the ice-sheet which deposited the grayish-black drift and the advance of the glacier which brought the red drift. The buff-weathered phase is present above the unaltered grayish-black till, and in some places this yellow oxidized till has been leached down five or six feet below

the contact with the overlying red till. Some cuts show a distinct erosion unconformity between the two drift-sheets.

At the present state of knowledge, the following drift-sheets have been recognized in the St. Croix–Dalles region:

1. A thin surface mantle of gray Wisconsin drift deposited by a glacier from the Keewatin center, as described in previous papers.

2. An upper red drift deposited by a glacier of Wisconsin age from Labrador, as similarly described.

3. A sheet of brownish-red to carmine-red sandy drift left by an ice-invasion coming from the Labrador center across the Lake Superior basin and extending as far to the south as the moraine at Hampton, Minn.; age consistent with Illinoian.

4. A sheet of dark grayish-black, calcareous, clayey till deposited by a vigorous advance of ice from the Keewatin gathering-ground and extending as far to the southeast as Hersey, Wis.; age probably Kansan, but still open to question.

"ROCK GLACIERS" OR CHRYSTOCRENES

J. B. TYRRELL
Toronto, Canada

In the number of the *Journal of Geology* for June, 1910, there is an interesting article by Stephen R. Capps, Jr., on "Rock Glaciers in Alaska" which must be of especial interest to all those who have lived in Alaska or in the Yukon Territory, and more particularly to those who have lived in the city of Dawson, for these latter will at once recognize the similarity of the rockslides described and illustrated by Mr. Capps to "the Slide" on the face of Moosehide Mountain at the north end of the town of Dawson, since the Slide is one of the outstanding and ever-present features of the landscape to every resident of that northern city.

The city of Dawson is situated on a swampy alluvial flat on the east bank of the Yukon River, just below the confluence of the Klondike River. About a mile to the northeast of it Moosehide Mountain rises to a height of 2,000 feet or more above the city, a spur of the mountain extending down to the Yukon River, and terminating the Dawson flat toward the north.

The mountain is composed of massive basic eruptive rock or diabase largely altered to serpentine, and cut by numerous jointage planes which allow the rock to break readily into angular fragments. Over the larger portions of the surface of the mountain the rock has been weathered and decomposed to a considerable depth, and has broken down into sand or rock flour, so that the natural slopes are consequently gradual and gentle. But on the southwest side of the mountain, directly overlooking the town of Dawson, there is a steep scarped face of bare rock several hundred feet in height, at the foot of which a talus of broken rock-fragments extends outward and downward toward the river. This talus extends so far outward from the foot of the scarp, and its lower portion has such a relatively gentle slope, that it has somewhat the appearance of having broken away suddenly from the side of the mountain; and consequently the early

miners attributed to the Indians a tradition that many, many years ago it had so broken away, and had buried an Indian village beneath it.

But it is not necessary to invoke any sudden landslide to account for this bare cliff and the great pile of loose rock at its base, since fragments of rock are even now constantly falling from the face of the scarp and adding to the size of the hill of rock-fragments below it.

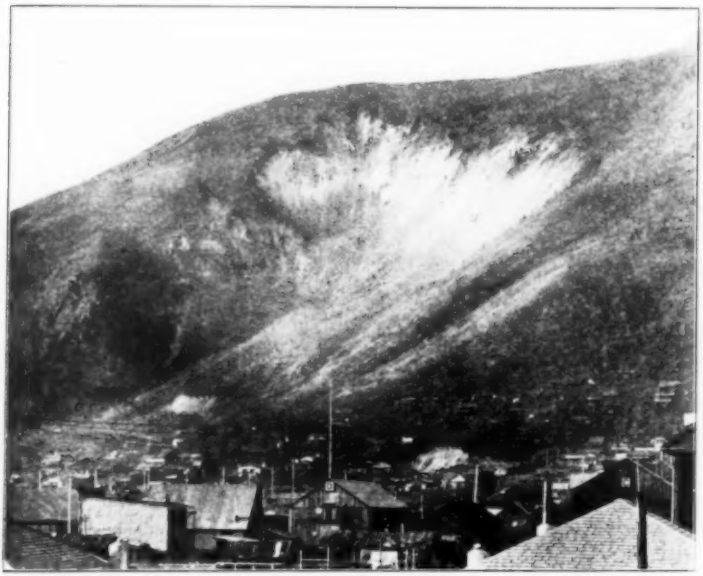

FIG. 1.—The Slide at Dawson.

The conditions which would seem to have combined to produce this naked scarp and the wide-spreading talus of broken rock at its base are somewhat as follows:

The general surface of the Yukon Territory in the vicinity of Dawson is permanently frozen for a depth of from 100 to 200 feet, beneath which the rock is more or less thoroughly saturated with water. In some places, and often on hillsides, this underlying water forms channels for itself through the frozen rock and soil, and breaks out as springs, and at the foot of Moosehide Mountain, directly

beneath the *slide*, one of these springs issues from the fractured serpentine. In the early days of the city this spring furnished the best supply of water for drinking purposes available in the vicinity.

During the summer season the water from this spring flows freely from the rock and down through the talus slope at the foot of the hill, but in winter, when the thermometer often drops to 50 below zero,

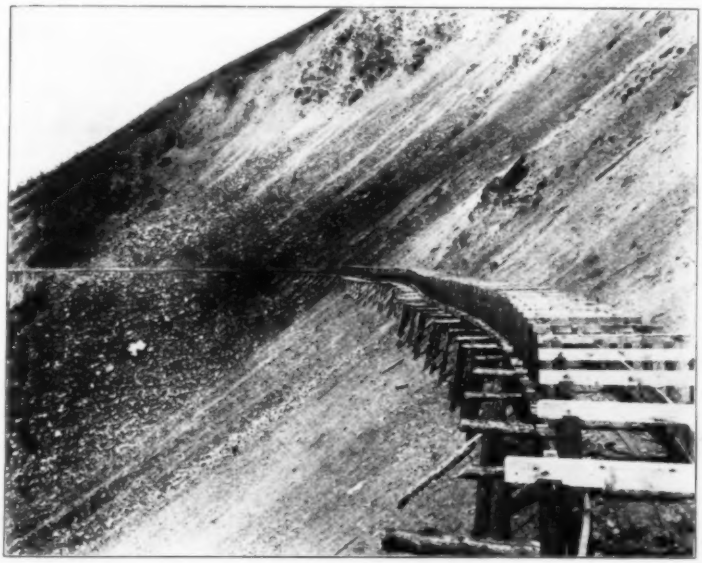

FIG. 2.—Upper part of the Slide at Dawson.

or lower, it freezes as it issues from the rock, or as it courses through the loose rock of the talus heap, and imbeds the broken fragments of rock in a matrix of clear, solid ice. At the same time loose pieces of rock are being constantly detached from the face of the hillside and dropped on this heap of rock-fragments lying below. In this way the heap of broken rock is being built up, and the weight of its higher side is being constantly increased. On account of this increase in weight, and also on account of the filling of the interstices between the rock-fragments with ice, there is a constant tendency for the pile of

loose rocks and ice to move downward and outward, and this tendency is increased in the spring and summer when the upper portion of the icy matrix becomes melted, so that the stones which were imbedded in it become loosened and slide downward over each other. This process of the breaking-down of the face of the almost vertical cliff and the growth and extension of the talus is constantly in operation year after year, so that the face of this hill of light-green serpentine always has the appearance of having just been freshly broken and the material at its foot of having just slidden from it, while the sloping field of loose rock below shows abundant evidence of having been recently moved to its present position.

We have here simply a northern modification of the conditions found on many hillsides where springs give rise to broken slopes.

In the *Journal of Geology*, XII (1904), 232, I described some springs which flow from the frozen hillsides in the Klondike and which in winter issue into the cold air, and are then almost immediately frozen into ice. During the course of the winter, these masses of ice may assume considerable proportions, and when they form on the roads or main lines of travel, they are often, on account of their smooth, sloping surfaces, the occasion of much inconvenience to the freighters and stage-drivers. In several instances they have also been known to break up in the floors of houses, and to fill the house with ice, just as they fill the spaces between the loose rocks in the heaps of talus. These frozen masses of spring water are, in the Klondike, locally known as "glaciers," but as this word was already fully preoccupied, I called them, on the suggestion of Professor T. C. Chamberlin, *chrystocrenes*.

The spring at the foot of Moosehide Mountain in Dawson forms one of these chrystocrenes, but instead of the water flowing out freely into the air, it flows into a detrital mass of broken rock and assists in gradually moving this rock outward from the foot of the mountain toward the Yukon River, which flows at its base.

I would suggest that the "rock glaciers" described by Mr. Capps may probably have been formed in the same way as the Slide at Dawson; that they are kept supplied with water flowing from springs in the sides of the hills; that this water becomes frozen into a mass of ice during the severe cold weather of winter; and that the ice, with

its contained fragments of rock, not only moves outward from the hills or mountains and down the valleys, but that when the upper parts of the ice melt under the influence of the warm weather in the spring, the rocks which were contained in it slide downward and form the concentric ridges which are so well shown in one of Mr. Capps's photographs.

The clear ice which constitutes the matrix for the mass of ice and stones in the talus is certainly not formed by the freezing of water during the warm weather of summer, when surface water is abundant, when streams are flowing in all the valleys, and when the temperature of the air often rises to 70° or even 80° F. It is equally certain that this icy matrix is formed during the winter, when, in the Klondike district, as well as in the interior of Alaska, the surface drainage is completely arrested, and the small streams are frozen to the bottom, and when the only water which reaches the surface is derived from springs with moderately deep-seated sources, though this spring water is quickly frozen into ice when it comes within the influence of the extremely low temperature of the overlying atmosphere.

The positions of these springs may readily be determined in winter time by the presence of chrystocrenes, which form more or less conspicuous mounds of ice elevated above the general snowy surface, but in the summer they are often very difficult to detect, for it may be impossible to distinguish between water derived from springs and that from surface drainage.

Therefore, the presence of the springs, and their possible significance in supplying ice to the talus heaps in order to enable these to move downward and outward more easily, would probably escape notice if investigations had been conducted exclusively in summer. Investigations conducted during the winter would probably prove the existence of springs behind these "rock glaciers," in which case they might be considered as chrystocrenes filled with broken fragments of rock.

ON A PECULIAR CLEAVAGE STRUCTURE RESEMBLING STRETCHED PEBBLES, NEAR ELLIJAY, GEORGIA[1]

W. C. PHALEN

INTRODUCTION

The subject of elongated or stretched pebbles has been treated in two articles by Mr. S. W. McCallie, state geologist of Georgia.[2] Both of the occurrences described are in Georgia, one of them, the first cited in the references below, being located in the vicinity of Ellijay, Gilmer County, about 75 miles north of Atlanta; the other 2½ miles southeast of Dahlonega, the county seat of Lumpkin County. Mr. McCallie's paper on the Ellijay occurrence may be summarized briefly as follows:

The stretched pebbles are chiefly confined to a belt less than one-half mile wide and about 15 miles long just west of the Louisville-Nashville Railroad and near the western margin of the crystalline rocks of the state. The beds containing the pebbles are in some places numerous. They vary from 1½ to 5 feet in thickness, and are always interbedded in mica schist. The pebbles in the different beds differ both in size and in degree of elongation. They are mainly found in a matrix of mica which, however, may be absent or nearly so, in which case the quartz pebbles may be welded together, requiring slight pressure to force them apart. Both quartz and feldspar pebbles are found, the former being the more numerous; the former also are greatly elongated while the feldspar pebbles retain more or less perfectly their original rounded shapes. The size, shape, color, and texture of the pebbles are next described, and the article closes with a description of thin sections of the pebbles. The title of Mr. McCallie's paper, "Stretched Pebbles from Ocoee Conglomerate," will serve to summarize sufficiently well his idea of the origin of the phenomenon.

[1] Published with the permission of the Director of the U.S. Geological Survey.

[2] *Jour. of Geology*, XIV (1906), 55–59; *ibid.*, XV (1907), 474–78.

During the past three summers the writer has had opportunity to study the metamorphic complex in the Dalton, Ellijay, and Dahlonega quadrangles at the northern edge of Georgia east of the Great Valley. Stretched pebbles,[1] so called, have been observed at various places in the first two areas mentioned. Among the localities visited and studied is that near Ellijay depot, as well as others not very far away from the town. As a result of these studies a possible different interpretation of this interesting phenomenon has been deduced. It is the object of this short sketch to present evidence for this interpretation of a phenomenon which, so far as the writer is aware, has never been observed elsewhere than in the southern Appalachians, or at least has never been described from any other region.

GENERAL GEOLOGY

The portion of the Appalachian Mountain belt near Ellijay probably consisted formerly of both sedimentary and igneous rocks. The region has passed through one or more periods of dynamic metamorphism as a result of compressive forces acting from the east or southeast. During this metamorphism and possibly since, the rocks were profoundly folded and faulted; simultaneously with and subsequently to these structural changes they have been altered and mineralized and as a result almost perfectly recrystallized. The erosion and weathering characteristic of the region as a whole, which followed the earlier forces, has left them in their present condition. The character of the rocks in the region varies widely from slightly metamorphosed slate to profoundly crushed and metamorphosed igneous and sedimentary rocks.

Location.—The first occurrence of "stretched pebbles" to be described is located near the town of Ellijay, the county seat of Gilmer County, near the confluence of Cartecay and Ellijay rivers. The "pebbles" may be found in a cut not more than 20 feet deep, on the railroad, 100 yards more or less north of the depot, almost opposite and also just beyond the new wholesale house of W. J.

[1] The term "stretched pebbles" is used for convenience in this and subsequent places. The writer's views as to the proper designation of these "pebbles" will be developed later.

Owenby & Co. This particular spot has been visited twice by the writer, first in the fall of 1907 and again two years later.

DETAILED GEOLOGIC RELATIONS

The cut is chiefly in the characteristic impervious surface or mantle clays of the region, and the "pebbles" are found in this clay, and in the slightly weathered country rock, found at the southwest end of the cut on the right side looking northeast. Those occurring in the country rock, however, are less perfectly developed than the others. The country rock is in the Great Smoky formation.[1] It is a greywacke and a weathered garnetiferous mica schist with the garnets largely altered to iron oxide. The schist is feldspathic. The rocks strike N. 20–45° E. and dip 50–60° S.E.

There are comparatively few or no signs of metamorphism in the rocks near Ellijay, which are extraordinary as compared with the general regional metamorphism, and such profound metamorphism as appears is generally quite local in development. At the location under discussion the rock has been so greatly crushed or subjected to such intense pressure that it does not break into massive blocks bounded by joint planes, but into long thin masses, resembling tapering lenses or stretched pebbles, overlapping when *en masse*, with excessive length as compared with their other dimensions. The illustration in Mr. McCallie's article[2] reveals the conditions well. At the south end of the cut these masses appear to be composed chiefly of quartz, and they will be found to crumble readily away from each other when removed from the ledge. When these quartz masses resembling stretched pebbles are thus separated, though some of the mica of the country rock falls away from them, considerable of it still adheres. Though many of these masses consist apparently of pure quartz, some of them contain or are largely made up of the micaceous portions of the country rock. All gradations between the two extremes may be observed. It is a fact, however, that the great bulk of the best

[1] The same units have been chosen for mapping in the Ellijay quadrangle as were adopted by Keith in the Nantahala area to the north ("Nantahala Folio, No. 143," *U.S. Geol. Survey*, 1907). Of course the same scheme has not been adopted in its entirety, for the obvious reason that some of the more marked lithologic types die out in passing to the southward.

[2] *Journal of Geology*, XIV (1906), 56.

examples of the "pebbles" are composed chiefly of quartz, excepting those produced from vein quartz to be described directly.

Traversing the country rock in all directions are quartz veins, true chemical segregations. Though formed subsequently to the rock in which they are found, they antedate, in this restricted locality, the period of metamorphism in which the pebbles described above were produced, for the reason that the structure has been produced in the quartz vein itself. Indeed it is from such material that the most perfect "pebbles" were obtained (see Fig. 1). The quartz veins in the railroad cut vary from a fraction of an inch up to 6 inches or more in thickness. Toward the northwest end of the cut under discussion, and just before the gradual curve to the right begins, will be found the best exhibition of the "pebbles." In the fall of 1907 one of the quartz veins could be traced fairly well across the cut, which at the time was thought to have furnished the bulk if not all of the best specimens. This evidence, however, is not at all conclusive at the present time, for on a more recent visit in the fall of 1909, this tracing could not be made at all, on account of slides in the clay in the cut. That the vein quartz has furnished the material for many of the lenses of "pebbles," however, can be shown from the specimens collected at the earlier visit, in which the gradation from the latter into the former is well brought out (see Figs. 2 and 3). In such hand specimens the quartz lenses may be picked out and replaced in their former positions, the whole appearing as a single solid mass when bound with an elastic band. Specimens were col-

FIG. 1.—A group of quartz lenses, resulting from pressure on vein quartz. Ellijay, Gilmer County, Georgia.

lected showing varying stages in the transition from the unfractured massive vein quartz to those in which the quartz pebbles were fairly well developed. Such specimens though less perfect examples of the structure itself are nevertheless instructive in that they show the

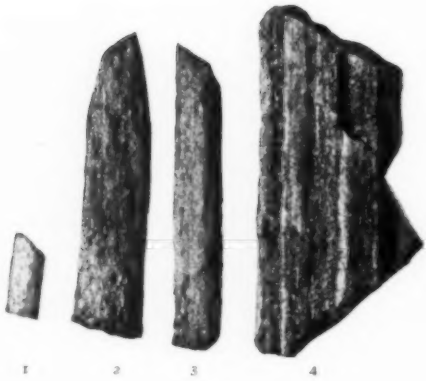

FIG. 2

FIG. 3

FIG. 2.—Group of quartz lenses. Lenses numbered 1, 2, and 3 have been separated from 4 and may be replaced in their former positions.

FIG. 3.—A bundle of imperfect lenses. The arrow indicates a lens about to break off.

intermediate steps in the transition of the massive rock to the lenticular or stretched pebble-like phase, and one method by which the latter may be formed.

OTHER OCCURRENCES

On the road which leads directly north from Ellijay up Ellijay River there is another occurrence of the structure (for such it may be regarded) described near Ellijay depot, about a mile and a quarter north of the town and about a quarter of a mile south of the road forks.

The rocks here strike N. 20–25° W., though the general strike of the region is to the east of north. Like the rocks at Ellijay depot, the country rock here may be classed as a feldspathic mica schist, in which there are secondary feldspar phenocrysts, badly weathered. The rock probably was arkose originally. As at Ellijay depot, there are associated quartz veins which here however postdate the metamorphic processes which produced the pebble-like structure, as the vein material does not show any particular tendency to break into lenses as at Ellijay depot. The phenocrysts of feldspar already referred to have probably formed since the crushing took place, as during their development they have pushed away the surrounding matrix which now curves about them. This latter hypothesis to the writer is a more plausible assumption than that the crushing processes have failed to affect them, for there is no reason to suppose that they would resist the crushing action more effectively than quartz. The joint planes in the rock cut squarely across the pebble-like quartzes and are therefore in part at least of later origin. The broadest band in which quartz lenses appear is fully 15 feet thick. A short distance farther up the hill are two thinner bands showing the phenomenon equally well with the 15-foot band, and the intermediate beds exhibit it, though less perfectly. Such highly metamorphosed bands are fairly common in this general region and good examples have been observed and specimens showing the structure collected north of the head of Kells Creek within the Ellijay area.

It is not so easy here to disprove the former existence of original true quartz pebbles and no attempt will be made to do this. It will simply be pointed out that the similarity of the occurrences to that near Ellijay depot is noteworthy, and that, as in the latter case, another hypothesis for the origin of the quartz masses is not only possible but probable.

DETAILED DESCRIPTIONS

It was thought that a study of thin sections of the rock showing the pebble structure might throw some light on the origin of the phenomenon. The results, however, are somewhat inconclusive. The sections of the "pebbles" do show evidence of profound crushing, but then either crushed true pebbles or vein material would exhibit similar features in thin sections. Instead of the crystalline outlines

characteristic of ordinary uncrushed vein quartz in thin sections (see Fig. 4), the sections are fine-grained mosaics with crystallographic boundary planes entirely absent (Fig. 5). Therefore the most important evidence of derivation from former vein material is absent. Even all signs of internal strain are lacking for the reason that the quartz like all the other rocks of the region has undergone almost perfect recrystallization, that is, molecular readjustment to

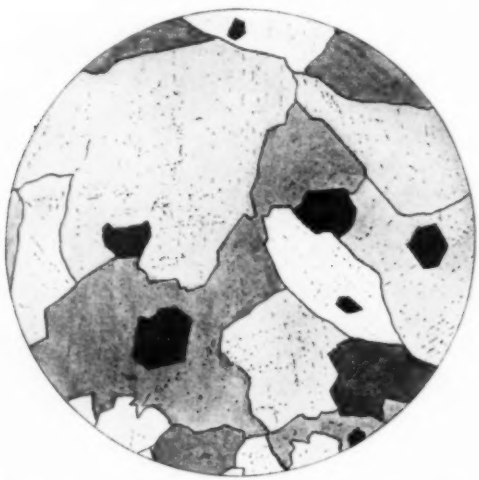

FIG. 4.—Normal structure in vein quartz. From the report of Waldemar Lindgren on the "Gold Quartz Veins of Nevada City and Grass Valley Districts, California." In *Seventeenth Annual Report, U.S. Geological Survey*, Part II (1896), Pl. IV, Fig. *a*, opposite p. 132.

the surrounding conditions. The actual tracing of the "pebble" structure, however, into the original quartz vein material is sufficient evidence for another explanation of the phenomenon.

The results of the examination of the thin sections are given below.

Several thin sections cut in various directions from the quartz masses were studied in polarized light under the microscope, to determine if possible how deformation took place. These sections were cut as follows: (1) normal to the direction of elongation of the pebbles; (2) parallel to the direction of elongation and to the major

axis of the approximately elliptical cross-section; (3) parallel to the direction of elongation and to the minor axis of the approximately elliptical cross-section.

The sections are all alike in showing the quartz masses to be essentially mosaics of irregularly shaped granular interlocking particles. In a word, the microscopic structure is typically that of crushed and recrystallized quartz. In the first set of thin sections

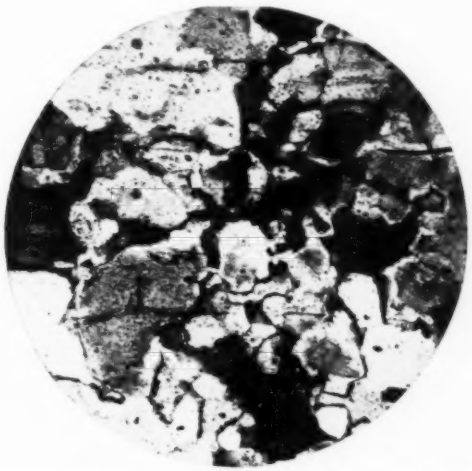

FIG. 5.—Micro structure of crushed vein quartz from near Ellijay, Ga. The lack of crystallographic boundaries is apparent.

examined, namely, those cut normal to the direction of elongation of the masses, the grains show dimensional, but not crystallographic parallelism. The longer axes of the grains, as would naturally be supposed, are parallel to the major axis of the elliptical cross-section. This may be and quite likely is due to deformation, but there are no evidences of deformation in sections cut parallel to the direction of elongation of the quartz masses, as might naturally be expected. If due to deformation producible by pressure normal to the direction of flattening, all evidence of internal strain, usually evidenced by wavy extinction, has disappeared, but this might readily be brought about by recrystallization. The perfect interlocking of the grains is

evidence of recrystallization. The molecular readjustment necessary to obliterate all traces of strain may have occurred while the rock was deeply buried, for it is almost certain that many of the phenomena associated with the rocks of the region could only have been produced while under very heavy load, i.e., while deeply buried, or subjected to great pressure, or both. But it seems that recrystallization by solution and redeposition is as adequate and as safe an explanation. That the rocks contained water is certain. The presence of muscovite and biotite as secondary minerals, and the evidences of the sedimentary origin of the rocks, all point to the former presence of water. The amount of water present may have been small, as the presence of large quantities of water to bring about such molecular changes as postulated above is not essential.[1]

In sections cut parallel to the length of the quartz masses, there are also evidences of crystallographic continuity, the larger part of the sections extinguishing in a given position. Finally in all the sections studied cracks were observed running parellel to the major axes of the cross-section and also parallel to the length of the quartz masses.

CONCLUSION

As a result of the studies made by the writer, it is concluded that there is no necessity for assuming the former presence of original quartz pebbles to produce the pencillate or pebble structure, or lens-shaped masses of quartz described above, for, as pointed out, the more perfect examples of the structure have been found resulting from quartz veins. That elongations in true quartz pebbles may occur and the results exactly resemble the structures figured above, is so obvious as hardly to necessitate mentioning here. The structure is regarded as essentially due to a peculiar cleavage combined with flow cleavage (recrystallization). It is quite likely that it may be produced in any rock and the simpler, the more resistant, and the more homogeneous the material, perhaps the more perfect the resulting structure. Such structures on a much larger scale have been observed by Mr. Arthur Keith of the U.S. Geological Survey, a few miles west of Canton, Ga. They are figured in the accompanying illustration (Fig. 6). The country rock here is a talc schist, and

[1] C. K. Leith, "Rock Cleavage," *Bull. U.S. Geol. Survey, No. 239* (1905), 63.

FIG. 6.—Elongated or lens-shaped masses of quartz, occurring in talc schist. Photograph of specimens collected by Mr. Arthur Keith, U.S. Geological Survey, near Canton, Georgia.

the elongated lens-shaped masses are essentially made up of quartz with an outer covering of the schist. They measure nearly 3 feet in length, with a breadth of 2 to 4 inches and a thickness of 1 to 2 inches. So far as appearances go, they closely simulate on a much larger scale the smaller masses collected near Ellijay. They cannot by any stretch of the imagination be regarded as stretched or deformed bowlders. Pogue[1] has figured and described almond-shaped masses of mashed acid coarse tuff from Davidson County, North Carolina. The rock, according to this writer, has undergone a moderate amount of compression and now projects above the ground surface in lenticular or almond-shaped masses 20 feet long, 10 feet high, and 5 feet thick at the base. They are distributed in groups and often scores may be seen in alignment following the trend of a tufaceous belt. It has occurred to the writer that Pogue's almond-shaped masses may be of the same nature as the structure observed near Ellijay, but on a gigantic scale. In conclusion, it is desired to emphasize the view that the Ellijay occurrences are purely structural phenomena producible in varying degrees of perfection in almost any rock, independent of original pebbles, and liable to occur in any region of intense metamorphism.

[1] *Am. Jour. Sci.*, XXVIII (September, 1909), 224.

Reviews

Soil Fertility and Permanent Agriculture. By Cyril G. Hopkins. 8vo. Pp. 23+653, ill. 14. Boston: Ginn & Co., 1910. $2.75.

This volume is a "summons and a challenge." It is dedicated to "The Association of American Agricultural Colleges and Experiment Stations, the rightful guardians of American soils." It is addressed to farmers and students of agriculture, who "have at least as good intellects as other classes of people." It is a book not written for entertainment, but to be studied, and it is well worth studying.

Part One has four chapters, largely foundation facts of chemistry; three chapters on soil formation, classification, and distribution; two chapters on soil survey and soil analysis by the United States Bureau of Soils, an excellent summary, with instructive maps; and three chapters on crop requirements in the principal soil compounds as plant foods. Part Two consists of six chapters devoted to permanent agriculture, showing the rôle of limestone, nitrogen, and phosphorus, the significance of rotation, and theories concerning soil fertility. Part Three is an excellent résumé of the best soil investigations by culture experiments, as carried on at Rothamstead, England, and at the leading American experiment stations, Pennsylvania, Ohio, Illinois, Minnesota, and others. Part Four is devoted to studies of various fertility factors; and the volume closes with an appendix of valuable statistical and other data ancillary to the text.

In the introduction the author says truly: "The most important material problem in the United States is to maintain the fertility of the soil, and no extensive agricultural country has ever solved the problem." And again, "If the art of agriculture has ruined the land, the science of agriculture must restore it, and the restoration must begin while some farmers are still prosperous, for poverty-stricken people are at once helpless, and soon ignorant, and poverty makes no investments."

The book is filled with the results of scientific studies, showing the elements removed from the soil by the growing crops, and the quantity there to be removed; showing the results of various fertilizers, and of various systems of rotation; showing that the key to permanent agriculture lies in phosphorus and decaying organic matter; and that good farming consists in an accurate bookkeeping with the soil.

It is shocking to learn that all the known phosphate deposits in the world will last at best only 250 years at the present rate of consumption; that America now furnishes two-thirds of the world's supply and sells half of it to foreign lands; while it would require our entire production of phosphates upon our own soil to give back to the soil what our corn crop alone takes from it.

The author is to be congratulated on producing a strong book in a very vital field. Its influence should be constructive in a high degree.

J. PAUL GOODE

Epitome of the Geology of New South Wales. By E. F. PITTMAN. Circular No. 9. Sydney: Mining and Geological Museum. 1909. Pp. 9. with geologic map.

This little pamphlet giving in a very brief, condensed form the principal features of the geology of this large Australian province has just come to the reviewer's attention. Those who frequently have occasion to familiarize themselves with the salient points in the geology of various portions of other continents often have longed for a series of just such outlines as this. To pick the desired information from separate volumes of a long array of standard geologic reports is a tedious and time-consuming task. A good map and the essential facts of a far-away country brought together and made available for ready use is a boon to every geologist who may have occasion to refer to that region. Now that geological studies are world-wide it is to be hoped that other countries and provinces will follow the example of New South Wales.

R. T. C.

Life and Letters of Josiah Dwight Whitney. By EDWIN TENNEY BREWSTER. Boston: Houghton Mifflin Co., 1909. Pp. 411. 18 illustrations.

In this biography the curtain is drawn aside and the reader is introduced intimately to one of the most conspicuous of the pioneers of American geology. When Whitney commenced his field work as an assistant on the first geological survey of New Hampshire in 1839, almost the whole of the United States was geologically an unknown land. The story of Whitney's life as it is unfolded in this book carries with it much of the history of several of the early surveys in which he took a leading part. These are the survey of the Lake Superior region (1847–50) which turned him from chemistry, toward which he had been preparing himself, to geology, and the Iowa State Survey, to which he was appointed in 1855 and which brought him

into active service in Wisconsin and Illinois as well. In 1854 appeared Whitney's *Metallic Wealth of the United States* which was the most notable work on the subject at the time.

With his fortieth year comes the end of the first of the three periods into which his life naturally divides itself. He has been by turn chemist, mining expert, geological surveyor, but never the single head of a survey. With the appointment as organizer and chief of the California Survey he is geologist and his own master.

The years in California were a period of ceaseless activity for Whitney, for the difficulties confronting this young survey in a new state of the dimensions of California were great. It was at this time that the youthful Baron von Richthofen came to California to study volcanic phenomena and became associated for a short time with the state survey. Out of this developed the lifelong friendship between these two geologists. Richthofen's geological survey of China was Whitney's idea, and the Baron often used to recall the New Year's Eve between 1867 and 1868 when he and Whitney sat up all night and planned the China Survey.

In 1874 the California Survey came to an end. Its termination apparently was due to a variety of causes. The survey had been from the first the project of a small group of enlightened persons, not the response to any popular demand, and its function and work were but poorly appreciated. In addition the survey earned the ill-will of many promoters, especially the oil companies, by steadily minimizing, with perhaps unnecessary directness and emphasis, the commercial possibilities of the California oil fields. Such a combination of causes—the bad financial status of the state, a general lack of insight and appreciation of scientific work by its influential people, the opposition of unscrupulous promoters, and an unfortunate cavalier tone and frequent want of tact displayed by the state geologist which stimulated general antagonism from the mining interests and from the governor—led to the final wreck of the survey.

The California Survey was in a way the pathfinder for the U.S. Geological Survey which was organized under King, Whitney's protégé, in 1879. The first director and some of his best-trained associates had received their geological training and field experience under Whitney. The methods of field work and topographic surveying adopted in California were later transplanted in the larger organization. The California Survey first shook the tree of which the federal survey has gathered up most of the fruit.

After such active pioneer field work and incessant travel for so many years, Whitney settled down for the latter part of his life as Sturgis-Hooper professor at Harvard. He did only a limited amount of teaching to small

advanced classes, but though his pupils were not numerous, they were picked men, and the list of those who were trained under him includes not a few of the leading geologists of the country today.

The story is chiefly told by his letters to his favorite brother, William Dwight Whitney—letters which reveal the man without the reserve which usually accompanied hm, and which portray in a very graphic and vivid style much of the history of early geological exploration in this country.

R. T. C.

Iowa Geological Survey, Vol. XIX, Annual Report, 1908. With Accompanying Papers. Des Moines, 1909. Pp. 806, 22 plates, 117 figures.

Coal is the principal topic of this volume. Besides the *Seventeenth Annual Report of the State Geologist*, Professor Samuel Calvin, it contains the following papers: "Mineral Production in Iowa in 1908," by S. W. Beyer, pp. 1–20; "Coal Deposits of Iowa," by Henry Hinds, pp. 21–396; "Fuel Values of Iowa Coals," by F. A. Wilder, with analyses of Iowa coals by James H. Lees and A. W. Hixcon, pp. 397–519; "History of Coal Mining in Iowa," by James H. Lees, pp. 521–88; "Coal Statistics," by S. W. Beyer, pp. 591–97; "General Section of the Des Moines Stage of Iowa," by James H. Lees, pp. 598–604; "The Carboniferous Section of Southwestern Iowa," by George L. Smith, pp. 605–57; "Bibliography of Iowa Coals," compiled by James H. Lees, pp. 659–87; "Peat Deposits in Iowa," by S. W. Beyer, pp. 689–730; "Bibliography of Iowa Peat," compiled by James H. Lees, pp. 731–33; "Flora of Northern Iowa Peat Bogs," by L. H. Pammel, pp. 735–77.

R. T. C.

Radioactivity and Geology. An Account of the Influence of Radioactive Energy on Terrestrial History. By J. Joly. Pp. 287, pls. 6, figs. 4. New York: Van Nostrand Co., 1909.

The discovery of radioactivity has opened the way for quite a new conception of many geologic phenomena. Fresh light has been thrown upon obscure and difficult problems, old explanations have been weakened or displaced, and alternative hypotheses have been framed to explain various phenomena. Radioactivity when first discovered appeared to have its chief interest in the domain of the physicist and the chemist. How vital a rôle it may yet prove to play as an active geologic agent, how wide a range of geologic processes it may yet be found to enter as a decisive

factor, has been brought out with a large measure of fulness in this new work by Joly. The first two chapters are chiefly an exposition of radioactivity from the historical, physical, and chemical standpoint. They lay the foundation for the geologic studies and the applications which follow. The third chapter gives data upon the occurrence and distribution of radium in the earth's surface materials and leads on to others in which some of the author's more notable inferences and speculations are set forth.

Radioactivity is made to appear as an agency of prime importance in the variations and fluctuations of underground temperature. A study based upon the rocks and underground temperatures of the St. Gotthard and Simplon tunnels is thought to show a distinct connection between the radioactivity and the temperature gradients in the earth. With less plausibility, the tendency of mountain ranges to develop along belts of thick sedimentation is assigned to the radioactivity of the buried sediments and the supposed consequent heating. Pushing the view still farther, the author even endeavors to explain the exigeant phases of the mountain structure of the Alps, such as the peculiar overlapping pile of recumbent folds as set forth by Lugeon, Schmidt, and others, by localized radioactive heating of the strata during the process of folding, and by a resulting upward shifting of the geotherms which is thought to enable the folded sediments above to be carried northward by the thrusts while the synclinal troughs beneath are becoming anchored in the growing viscosity of the medium. The idea is suggestive, but it lays a heavy tax on the new agency.

The chapter on "Radioactivity and the Interior of the Earth" and the one following set forth the possibilities of radioactivity as a more profound source of the thermal energy of the globe; however, the author believes that the radium of the earth is largely concentrated in the outer 12 to 15 kilometers of the crust.

Strutt has estimated the age of various sedimentary beds by determining the amount of helium which they contain and comparing this with the rapidity with which this gas is developed from the radioactive materials present. He reaches the conclusion that the Carboniferous must date back above 140,000,000 years, as a minor limit, and the Huronian probably 400,000,000 years. Though a most enthusiastic supporter of the great importance of radioactivity as a geologic agent and as a clue to the unraveling of geologic history, Joly is inclined to place greater reliance upon estimates of the age of the earth based upon denudation, and upon the saltness of the sea, than upon those based upon the radium and helium content of the sedimentary deposits.

The book bristles with new suggestions, and as such is a contribution of stimulating value. Necessarily, however, many of the conclusions thus put forth somewhat tentatively must be received with reserve.

R. T. C.

The Whitehorse Copper Belt, Yukon Territory. By R. G. McConnell. Canada Department of Mines, Geological Survey Branch, 1909.

These very interesting copper deposits are located in the southern part of the Yukon territory, extending along the valley of the Lewes River for a distance of about twelve miles. The rocks of the district are limestones probably belonging to the Carboniferous period, cut by three sets of intrusions of Mesozoic age. Of these the second set, consisting of granites and granodiorites, are economically important. Overlying these rocks are basalt flows belonging to the Tertiary, and glacial silts and bowlder clays.

The ore deposits are all contact metamorphic in origin, chiefly in the limestone along its contact with the granite. Two types of deposits are noted, the magnetite ore bodies and the siliceous ore bodies. In the former, the chief minerals are magnetite, bornite, chalcopyrite, serpentine, calcite, clinochore, rarely pyrrhotite and sphalerite. In the latter, associated with the ore minerals, bornite and chalcopyrite, are andradite, augite, tremolite, actinolite, epidote, and calcite. The granite itself is mineralized for some distance from the contact, the same minerals being developed as in the limestone. The deposits are peculiar in having bornite as the principal ore mineral, and in having little or no secondary sulphide enrichment. The values in copper range from 3.20 per cent to 12.90 per cent, the richest being from the Valerie Mine, in which bornite is absent and chalcopyrite is the only known copper sulphide present.

E. R. L.

Eighteenth Annual Report of the Bureau of Mines, Ontario, 1909. Vol. XVIII, Part I.

The Report contains the following papers: "Statistical Review, by Thos. W. Gibson, Deputy Minister of Mines, pp. 5–78; "Mines of Ontario," by E. T. Corkill, Inspector, pp. 79–140; "Iron Ranges of Nipigon District," by A. P. Coleman, pp. 141–53; "Iron Range North of Round Lake," by E. S. Moore, pp. 154–62; "Black Sturgeon Iron Region," by A. P.

Coleman, pp. 163–79; "Bog Iron on English River," by E. S. Moore, pp. 180–95; "Geology of Onaman Iron Range Area," by E. S. Moore, pp. 196–253; "Iron Formation of Woman River Area," by R. C. Allen, pp. 254–62; "Lake Abatibi Area," by M. B. Baker, pp. 263–83; "Lake Ojibway; Last of the Great Glacial Lakes," by A. P. Coleman, pp. 284–93; "Classification and Nomenclature of Ontario Drift," by A. P. Coleman, pp. 294–97.

E. R. L.

The Yakutat Bay Region, Alaska. U.S. Geological Survey Professional Paper 64. 1909.

Physiography and Glacial Geology. By RALPH S. TARR; and *Areal Geology*, by RALPH S. TARR and BERT S. BUTLER. 183 pages.

Yakutat Bay lies about forty miles southeast of Mount St. Elias, and is the only break in a straight coastline of about three hundred miles. To the west is the great Malaspina Glacier, while numerous large glaciers occupy the region about the head of the bay. Of these the Hubbard Glacier is probably the finest example of a tidal glacier on the North American continent. The mountain region northward from the bay is described as a vast snow-covered area from which hundreds of angular peaks project, while the valleys are flooded with ice, giving rise to an ice drowned topography, from which valley glaciers extend toward and in some cases to the sea. The condition is so different from normal valley glaciation that a special name, "through glacier," is proposed. The glaciers are in a stage of retreat which has apparently been in progress for a considerable length of time. A marked change, in the nature of paroxysmal thrust affected at least four of the glaciers, mainly in the ten months preceding June 1906. As interpreted by the author, this was probably due to the shaking-down of great avalanches of snow onto the upper part of the glaciers by the earthquake of 1899. The description of the glaciers, glacial erosion, and glacial deposits takes up the greater part of the volume.

The rocks of the district are almost barren of fossils and have been subjected to profound disturbance. Four distinct groups are recognized, a complex series of granites, gneisses and schists, the Yakutat group of conglomerate shale and sandstone, probably Mesozoic, Tertiary sandstones, shales and clays, and glacial gravels.

E. R. L.

Reports on a Portion of the Algoma and Thunder Bay Districts, Ontario, by W. J. WILSON, and *On the Region Lying North of Lake Superior between the Pic and Nipigon Rivers, Ontario*, by W. H. COLLINS. Canada Department of Mines, Geological Survey Branch, 1909.

In the region covered by the first report the rocks are chiefly Laurentian, consisting of granites and gneisses. These are interrupted in considerable areas by hornblende and biotite schists with diabase dikes, which are classed as Keewatin. Microscopic descriptions of these rocks made by G. A. Young are given. In the north of the region are nearly flat-lying dolomitic rocks classed as Cambro-Silurian and Silurian. A list of fossils from these formations identified by J. F. Whiteaves is appended.

The entire region covered by the second report is composed of pre-Cambrian rocks, all of which are crystalline except in the west, where comparatively unaltered sediments are to be seen. According to lithological characters the rocks are placed in four groups: (1) Laurentian, an intimate association chiefly of granites and gneisses of various sorts; (2) Keewatin, dark green, gray, or black schists largely eruptive in nature, and sheared porphyries containing much secondary chlorite and pyrite; (3) Keweenawan, brick-red dolomites; and (4) eruptives, hornblende and eleolite syenites, diorite, pegmatites, and diabases.

Minerals of economic importance occur in considerable variety but few deposits of valuable extent have been found.

In both reports considerable attention is given to the routes followed and the rock exposures studied.

E. R. L.

The Coal Fields of Manitoba, Saskatchewan, Alberta and Eastern British Columbia. By D. B. DOWNING. Canada Department of Mines, Geological Survey Branch, 1909.

This report is a concise statement of the area and probable contents of the various coal fields of the middle portion of Canada. There are three important coal-bearing formations, all belonging to the Cretaceous period and separated by shales of marine origin. These are the Kootanie, the Belly River or Judith River (Montana), and the Laramie. The character of the coal ranges from lignite to anthracite, the anthracite area being that of the Cascade basin. The areas in which coal is to be found are described briefly; analyses already published are collected in the form of tables and selected analyses of other North American and foreign coals are added for comparison.

E. R. L.

Petrological Abstracts and Reviews

Edited by ALBERT JOHANNSEN[1]

Clarke, F. W. "Analyses of Rocks and Minerals from the Laboratory of the U.S.G.S.," *Bull. U.S. Geol. Survey No. 419*. Pp. 315. 1910.

Bulletins 220 ("Mineral Analyses") and *228* ("Analyses of Rocks") are combined in this edition and brought up to date. The conventional form of stating analyses is retained and the same method of treatment is followed. New Analyses: igneous rocks 56; sandstones, cherts, and sinters 21; carbonate rocks 39; slates and shales 3; soils, etc., 21; minerals 93. With these additional analyses there is a reduction of 169 pages which gives a large amount of valuable information in a small, compact bulletin.

Charles J. Hares

Dale, T. Nelson. "The Granites of Vermont," *Bull. U.S. Geol. Survey No. 404*. Pp. 133, pls. 5. 1909.

This work is a companion bulletin to those on the granites of Maine (No. 313), and of Mass., N.H., and R.I. (No. 354). Its method of treatment is both scientific and economic.

Part I. Geographically the granitic areas extend in a northeasterly direction between the central Green Mountain axis on the west and the Connecticut River on the east for almost the entire length of the state. The granites are of three types: (1) biotite granite, as that at Barre; (2) quartz monzonite, as that at Bethel; and (3) hornblende-augite granite—the "olive-green syenite" of Daly—as that from Mount Ascutney. The age of the Ascutney granite is placed as post-Carboniferous or pre-Cretaceous, that on the west side of Green Mountain as late Devonian or Carboniferous, and the traversing dikes as possibly Triassic. The author's conclusions are based largely on the works of Richardson and Daly.

Special points emphasized are: double sheeted structure, that is, a structure with horizontal jointing; compressive strain, which is illustrated by the elliptical shape assumed by the drill holes; schist inclusions; con-

[1] Abstracts may be sent to Albert Johannsen, Walker Museum, The University of Chicago, Chicago, Ill.

tact metamorphism (at Bethel the magma under pressure sent out stringers into the wall rock; at Barre, the constituent elements, quartz, feldspar, biotite, pyrite, apatite, etc., were injected as heated vapors along the cleavage foliation); orbicular texture in granite at Bethel—the nodules occur in sheets parallel to the flow structure and the major axes of the disks are parallel to the micaceous flowage bands; and delimonitization on the under side of the sheets of granite.

Part II, while chiefly economic, touches on the general geology of the areas, gives petrographical descriptions of rocks, and economic details of the quarries. The work concludes with a bibliography of the literature on granites and a glossary of rock and quarry terms.

CHARLES J. HARES

DALY, REGINALD A. "Average Chemical Compositions of Igneous-Rock Types," *Proc. Amer. Acad. Arts and Sci.*, XLV (1910), 211–40.

Using Osann's "Beiträge zur chemischen Petrographie" and a few other sources, the average chemical composition of 98 principal igneous-rock types (excluding ascitic dikes) has been calculated. The results are shown in a table which also gives the averages for the same rocks regarded as anhydrous. These averages are of use in showing the chemical "center-points" in Rosenbusch's classification, the one in general use by the makers of geological maps. The averages furnish one of the bases for finally calculating the "average igneous rock." The relative uniformity in the soda percentage of the more abundant types is specially noted in its bearing on the origin of oceanic sodium and, therewith, on the problem of the age of the earth. The striking similarity of the average granite analysis to the average analysis of the base (ground-mass) in augite andesite, and the equally close resemblance of the average diorite analysis to the arithmetical mean of average basalt and granite are illustrated. The table of averages shows that the effusive rocks are more salic than the corresponding plutonics, helping to prove the justice of Rosenbusch's primary subdivision of igneous rocks into deep-seated types and surface lavas. The difference is explained genetically. Other special points in classification are noticed. The essential identity of the averages for pre-Cambrian and post-Cambrian granites is referred to the "anchi-eutectic" nature of the type.—(AUTHOR'S ABSTRACT.)

DALY, REGINALD A. "Origin of the Alkaline Rocks," *Bull. Geol. Soc. America*, XXI (1910), 87–118.

No alkaline province can be described as free from subalkaline eruptives, especially those of basaltic or granitic types. Emphasis is laid on the indisputable fact that the visible volume of all alkaline rock bodies is a very minute quantity as compared with the visible volume of subalkaline eruptive bodies. An inductive study shows that most alkaline rocks cut thick masses of limestones, dolomites, or other calcareous sediments. A long table illustrates the association. This fact suggests the hypothesis that the absorption of carbonate disturbs the chemical equilibrium of subalkaline magma in such manner that alkaline fractions are produced by differentiation. Most of the alkaline species are ascribed to the interaction of basaltic magma and limestone (or dolomite), but more acid magma is also sensitive to the solution of carbonate. The hypothesis explains the concentration of alkalies; the desilication shown by the crystallization of nephelite, leucite, corundum, etc.; the extreme variability of alkaline bodies in mineralogical and chemical composition; the occurrence of such lime-bearing minerals as melilite, scapolite, wollastonite, melanite, etc., and CO_2-bearing minerals as cancrinite and primary calcite. Suggestions are offered as to some of the chief physico-chemical reactions involved.—(AUTHOR'S ABSTRACT.)

GEORGE, R. D., State Geologist, and Others. *Colorado Geological Survey, First Report*, 1908.

The report contains the following papers: "The Main Tungsten Area of Boulder County," by R. D. George, with notes on the intrusive rocks by R. D. Crawford, pp. 7–104; "The Montezuma Mining District of Summit County," by H. B. Patton, pp. 105–44; "The Foothills Formations of Northern Colorado," by Junius Henderson, pp. 145–88; "The Hahns Peak Region, Routt County" (an outline survey), by R. D. George and R. D. Crawford, pp. 188–229.

"The Tungsten Area of Boulder County." The ores are found in veins in a region of biotite granite and granitic gneiss, the latter grading into quartz-mica schist and mica schist. These older rocks are cut by dikes and irregular bodies of granite and both coarse and fine pegmatite. In the northern and western parts of the district are many dikes which are described by R. D. Crawford as dacite, latite, latite porphyry, andesites of various sorts, diabase, basalt, basalt porphyry, lamprophyre, pyroxenite, and limburgite.

"The Montezuma Mining District." The schistose rocks are described as the Idaho Springs Formation and the Hornblende Gneiss Series. In the former, quartz, biotite, and sillimanite are the most abundant minerals, the most characteristic rock being called a mica-sillimanite schist. The igneous rocks include three types of granite, porphyries of various sorts, aplites, pegmatites, and a diabase. The ore deposits occur in several of these rocks but their genetic relationships are not determined.

"The Hahns Peak Region." The igneous rocks include effusive rocks and dikes ranging from rhyolite to olivine basalt, with plutonic diorite and gabbro. Quartz basalt is found in several dikes in the western part of the district. Extreme contact metamorphism is developed at the contact of the porphyries with the sedimentary rocks. E. R. LLOYD

HALLE, G. "Neuer Hand-Demonstrationsapparat für alle Erscheinungen der Doppelbrechung im Kalkspat," *Zeit. Kryst.*, XLVII (1910), 376–77.

Describes an apparatus for the demonstration of double refraction; the calcite prisms are smaller than those generally used, the desired effect being obtained by the use of a magnifying glass. For class work, the instrument is provided with a dicroscope and an aperture for mica wedge.
W. T. SCHALLER

LEISS, C. "Mikroskop mit gemeinsamer Nicoldrehung in vereinfachter Form," *Zeit. Kryst.*, XLVII (1910), 377–78. Fig. 1.

A simple arrangement, suggested by Dr. F. E. Wright, by which both nicols can be simultaneously rotated by means of a rigid vertical bar.
W. T. SCHALLER

MACKIE, WILLIAM. "The Distribution and Signification of Deviations from the Normal Order of Crystallization, also the Distribution and Significance of Micropegmatite in Granites, as Illustrated by the Granites of the North of Scotland." *Trans. Edinburgh Geol. Soc.*, IX (1909), 247–317. Diagrams 6, photomicrographs 8.

The author found in previous microscopic investigations of granites from the north of Scotland, that deviations from the normal order of crystallization existed in almost every rock-slide examined, and the occurrence of patches of micropegmatite was far more frequent than indicated in previous descriptions of such rocks. The present research was undertaken

to obtain data as to the order of crystallization, the occurrence and distribution of micropegmatite, and, if possible, to arrive at some definite conclusions as to the origin and causation of the observed phenomena.

The author recognizes three kinds of micropegmatite: (*a*) intergrowths developed in the regular course of crystallization, (*b*) centric or radial forms developed in connection with and radiating from the edges of the feldspars, and originating in the reactions between the various minerals in contact with it, and (*c*) the form of micropegmatite presented by the matrix in which the other minerals are imbedded. From 182 slides examined, representing 90 different rocks, it was found that type *a* occurred in 23.3 per cent, *b* in 68.8 per cent, *c* in 13.3 per cent, and absence of any form of micropegmatite in 17.7 per cent.

In examining the sequence of crystallization the author found that any two minerals, whose periods of crystallization overlap, even where one of them is crystallizing at an abnormal period, may appear in micropegmatitic intergrowth; and the relative frequency of occurrence of any single pair in such combination is in proportional relation to the general coincidence of the crystallization periods of the particular minerals entering into the combination. Besides the usual intergrowths of quartz and orthoclase, the author found intergrowths of quartz and hornblende, orthoclase and hornblende, plagioclase and hornblende, sphene and hornblende, magnetite and hornblende, biotite and hornblende, quartz and biotite, orthoclase and biotite, plagioclase and biotite, quartz and plagioclase, orthoclase and plagioclase, quartz and microcline, microcline and plagioclase, quartz and sphene, plagioclase and sphene, orthoclase and sphene, biotite and sphene, quartz and epidote, and epidote and orthoclase.

All the phenomena are most readily explained on the theory of the origin of granite by crystallization from solution. The process is not always progressive, but at certain stages reversions come in and partake of the nature of re-solution of parts that had already become solid.

In conclusion the author gives in detail the various stages that appear to be indicated in the crystallization of a granite, and considering that the normal biotite granites have been derived by differentiation from a hornblendic magma, he gives the following stages for all granites: (1) At a temperature probably somewhat above 1,100° C., hornblende began to crystallize. (2) In supersilicated hornblendic magmas, quartz, orthoclase, and an acid plagioclase, or any combination of them, may appear along with the last of the hornblende, the appearance of these minerals in this connection being apparently due to their solubility in the originally liquid hornblende. (3) Partial resorption of these minerals, and in particular of

orthoclase, may occur, apparently in consequence of the heat liberated by the crystallization of the hornblende. (4) Crystallization of sphene, sometimes simultaneous with, sometimes previous to, the hornblende, and in some cases even somewhat later, and at times around previously separated and partially resorbed quartz, orthoclase, and plagioclase nuclei. (5) Crystallization of biotite, with occasional resorption of hornblende—probably in consequence of, or at least aided by, the heat liberated by the crystallization of the biotite, with the subsequent separation of more quartz; but independently of this, quartz, orthoclase, and plagioclase may also appear in connection with biotite for the same reason that they appear in connection with the hornblende, viz., from solution in the originally liquid biotite. (6) Crystallization of plagioclase with occasional resorption of some of the biotite, with subsequent liberation of magnetite. (7) Crystallization in supersilicated magmas of part of the quartz, often as micropegmatite of the *a* type along with plagioclase, and later, in like manner, with orthoclase also. (8) Crystallization of orthoclase, with solution, in part, of the plagioclases, apparently from heat of crystallization of the orthoclase with subsequent development of micropegmatite of *b* type in the areas of solution. (9) Solution also, in part, of the earlier orthoclases during the crystallization of the later orthoclases, also with development of micropegmatite of *b* type in the areas attacked. (10) Crystallization of remaining portion of quartz with little or no action on the previously crystallized minerals. (11) Crystallization of microcline if present, with partial solution of plagioclases and orthoclases—the latter in limited degree—with subsequent development of micropegmatite of *b* type in the areas of solution. (12) Crystallization of remaining liquid magma, if any, with varying conditions, occasionally as micropegmatite of the *c* type, occasionally as microgranite.

ALBERT JOHANNSEN

NIKITIN, W. "Drehbarer Compensator für Mikroskop," *Zeit. Kryst.*, XLVII (1910), 378–79. Fig. 1.

Describes a sensitive instrument for measuring weak double refraction.

W. T. SCHALLER

NIKITIN, W. "Halbsphäroid zur graphischen Lösung bei Anwendung der Universalmethode," *Zeit. Kryst.*, XLVII (1910), 379–81. Fig. 1.

An apparatus to replace the stereographic net. Used in connection with a Fedorow Universaltisch, the optical constants may be directly drawn, with a pencil, upon the unglazed porcelain surface of the half sphere.

W. T. SCHALLER

NOBLE, L. F. "Contributions to the Geology of the Grand Canyon, Arizona, The Geology of the Shinumo Area, (continued), Part II," *Am. Jour. of Sci.*, iv ser., XXIX (1910), pp. 497–528. Pl. 1.

The writer gives a detailed description of the stratigraphy and lithology of the Unkar (Algonkian) rocks of the area. The sedimentary rocks consist mostly of alternating shales and quartzitic sandstones with some slate and considerable thicknesses of limestone.

The diabase intrusions described are of special interest. A sill of from 650 to 950 feet in thickness is intruded above one of the limestone members. Below this intrusive occurred large amounts of serpentine in bands and nodules. These show no trace of an alteration structure which might indicate a derivation from pyroxene, hornblende, or olivine. This fact and the fact that serpentine and asbestos are not developed within the diabase itself lead the author to believe that they are the result of contact metamorphism, conditioned by the invasion of the limestone by the diabase. The diabase itself consists primarily of plagioclase feldspar (near labradorite) and olivine in about equal amounts, with a subordinate quantity of augite and brown biotite. Ophitic intergrowths of augite and plagioclase occur throughout, and pegmatite dikes cut the mass.

At one point the rock at its upper contact is a pink hornblende syenite which appears to grade downward into the normal diabase. Transition specimens were not collected and the author's suggestion that the syenite is due to differentiation in place is only tentative.

A map showing the distribution of Algonkian rocks in the Grand Canyon region is appended.

ALBERT D. BROKAW

PARSONS, A. L. "Ein neues Sklerometer," *Zeit. Kryst.*, XLVII, (1910), 363–70. Figs. 2.

Describes a new instrument for measuring hardness, giving the construction and adjustments of the instrument and a few comparative results.

W. T. SCHALLER

RANSOME, F. L. "Notes on Some Mining Districts in Humboldt County, Nevada," *Bull. U.S. Geol. Survey No. 414.* Pp. 71. 1909.

These notes are based upon reconnaissance work. With the exception of a small portion, the field had been previously geologically mapped by the Fortieth Parallel Survey. In general, the granites described as Archean by that survey are intrusives in Mesozoic rocks; many of their Triassic

quartzites are rhyolites, and thorough study would probably change many of the names applied to the igneous rocks. Some are pre-Tertiary, but most of them are Tertiary in age. Among the effusives are andesites, rhyolites, basalts, tuffs, and breccias. The granular rocks occur less abundantly. Those mentioned are granodiorites, hornblende-gabbros, diorites, monzonites, micaceous granites, granite- and diorite-porphyries.

The paper concludes with a list of minerals found in the district.

CHARLES J. HARES

SPITZ, ALBRECHT. "Basische Eruptivgesteine aus den Kitzbüchler Alpen," *Tscher. Min. Petr. Mit.*, XXVIII (1910), 497–534.

In the so-called Silurian schists of the Kitzebüchlian Alps, occur two groups of basic eruptive rocks. One group consists of undoubtedly effusive sheets and tuffs, interbedded with the schists; the other consists of isolated outcrops whose mode of occurrence is indeterminable.

The rocks described are monzonite-diabase, ordinary and olivine diabase, diabase porphyrite, hornblende diabase (proterobase), hornblende picrite, proterobase amygdaloid, albite-chlorite schist, and epidote-chlorite schist. The rock of greatest interest is the one to which the writer gives the name of monzonite diabase. With this term he wishes to designate all rocks which carry potash feldspar in greater quantity than is normal in diabases, but does not say that the amounts of orthoclase and plagioclase must be equal. Brauns and Erdmannsdörfer have previously described rocks which contain greater amounts of potash and which are transitional to essexites and theralites. The monzonite diabases differ from essexite- and theralite-diabases in the greater amount of SiO_2 in the former, so that they are sometimes quartz-bearing and are then related to Kongadiabase.

The plagioclase in the monzonite diabase is almost pure albite, which the author says is only comprehendable by considering it due to alteration. The potash feldspar occurs in part in irregular patches in the plagioclase, in part as interspaced filling. Much of it is peculiar in having a small axial angle, $2V=48°$, and in being optically positive. The pyroxene is enstatite augite (Mg-diopside of Rosenbusch), and is sometimes intergrown with brown hornblende. Ilmenite is present and there is much apatite. The texture is divergent-strahlig-körnig (Lossen's term for ophitic). The iron minerals and apatite were the oldest, and quartz and micropegmatite the youngest minerals to form. Pyroxene and feldspar are essentially of the same age, for they mutually inclose each other.

A chemical analysis of a quartz-free monzonite diabase from Weissenbachtal near Ellmau gives: SiO_2 49.86, Al_2O_3 13.01, Fe_2O_3 13.78,

MgO 3.50, CaO 7.26, Na_2O 4.00, K_2O 1.66, H_2O 2.08, TiO_2 0.69, P_2O_5 0.38, CO_2 2.08=99.45. The rock is considerably altered and its computation is difficult. According to Osann's system it shows: $s=58.3$, $a=3.5$, $c=1.9$, $f=14.6$, $n=7.9$, $k=0.90$. It is related to the Kongadiabase of Hartenrod near Herborn, the diabase from Rocky Hill, New Jersey, the Hunnediabase from Campo Santo, the Hunnediabase from Halleberg, and the diabase from Richmond, Cape Colony.

(The rock is an alkali diabase or an orthoclase-albite diabase).

ALBERT JOHANNSEN

UHLEMANN, ALFRED. "Die Pikrite des sächsischen Vogtlandes," *Tscher. Min. Petr. Mit.*, XXVIII (1909), 415–72. Maps 1, figs. 17, photomicrographs 8.

The picrites here described occur in surface flows, dikes, and intrusive sheets, and are generally associated with granular diabases. The period of eruption began at the end of the Silurian and ended before the beginning of Middle Devonian.

The author particularly examined the relations between the picrites and the diabases, for, according to Rosenbusch, picrites are feldspar-free olivine diabases, and picrite porphyrites are feldspar-free melaphyres, and there are gradations from one to the other. The present study does not confirm this. An analysis was made of the normal diabase, another of the same rock near the contact, and a third of the picrite near the contact, and while there is an enrichment of magnesia in the contact diabase, this is explained by the assimilation of fragments of the picrite through which the diabase was erupted. The author believes that the cause of the association of diabase and picrite is not to be found in differentiation after eruption, but in intratelluric differentiation from a single magma.

In habit the picrites are coarse granular (½–2 cm.), more rarely medium-grained (2–4 mm.), pyroxene-olivine rocks, with less amounts of iron ores and apatite, and rarely basic plagioclase. Locally there is found primary biotite, rhombic pyroxene, or a globulitic and trichitic intersertal basis.

Two analyses of the picrites were made by the author and an older one from Gümbel is given for comparison. All of them are computed in Osann's system and the following formulae are found:

$$S_{44.8},\ a_0,\ c_1,\ f_{10},$$
$$S_{27}\ ,\ a_0,\ c_1,\ f_{10},$$
$$S_{42.1},\ a_0,\ c_1,\ f_{10},$$

which shows a remarkable resemblance between the three specimens from widely separated areas.

Three types of picrite are distinguished according to texture: (1) hypidiomorphic-granular (all the analyzed specimens belong to this group); (2) holocrystalline-porphyritic rocks with hypidiomorphic-granular groundmasses; and (3) hypocrystalline-porphyritic rocks with intersertal groundmasses.

Since such different textures are included among the picrites, the author proposes for the third type, from its occurrence at Altschönfels, the name of "Schönfelsit." In composition, Schönfelsite is a porphyry with closely crowded phenocrysts (persemic) of olivine and augite in a megascopically aphanitic ground-mass. Microscopically this ground-mass is seen to consist of rare apatite, aggregates of titaniferous magnetite, granular augite, long prismatic crystals of bronzite, automorphic laths of bytownite-anorthite (sometimes anorthite), and a gray or brown devitrified basis. The occurrence of basis in picrite is noteworthy and points to the effusive nature of the occurrence. This basis fills the interstices between the divergent laths of feldspar and also occurs between the pyroxene grains as a distinct interstitial filling. It is completely made up of fine scaly particles of a chloritic aggregate in which there still remain well-preserved trichites and globulites.

There are numerous secondary minerals found in the picrites described. They are tremolite, uralite, antigorite, bastite, pseudophite, pennine, delessite, prochlorite, talc, dolomite, siderite, epidote, kaolin-like products, and magnetite. ALBERT JOHANNSEN

TUTTON, A. E. H., *Crystalline Structure and Chemical Constitution*. London: Macmillan, 1910. Pp. viii + 200, figs. 54. $1.50 net.

The title of this book is perhaps a little misleading, as it is not a general treatise on the subject, but is rather, as is stated in the Preface, an effort to present in a concise manner the author's original contributions to the subject of the relation between the form, structure, and physical properties on the one hand, and the chemical composition of the substances on the other.

The first four chapters are devoted to a historical sketch by way of introduction. The Haüy-Mitscherlich controversy on isomorphism is reviewed in its relation to more views on the subject. In a discussion of the periodic classification of the elements in its relation to isomorphism, the author digresses for a moment to decry the growing usage of oxygen = 16 instead of hydrogen = 1 as a basis for atomic weights. His reasons seem to be sentimental rather than practical, as chemists in general are agreed as to the advantages of the former.

After an instructive introduction to the study of isomorphous series the author proceeds to describe improved apparatus that he found it necessary to devise before his measurements could be made with the required precision. Perhaps the most important of these is a cutting and grinding goniometer. By means of this instrument it is possible to cut truly plane surfaces, oriented with almost mathematical accuracy. Either parallel-faced sections or 60° prisms may be cut by changing appliances. The instrument and its operation are described in detail.

A spectroscopic monochromatic illuminator for use in the study of the optical properties is substituted for the usual Na-light, K-light, Li-light, etc., with very satisfactory results. It involves little that is new in principle, though considerable ingenuity is expressed in the mechanical details. In a dilatometer for measuring the expansion of variously oriented sections, and in an elasmometer for the study of the elastic properties the well-known interferometer method of measuring minute distances is employed with gratifying results.

After describing his apparatus the author takes up a discussion of his own studies of two isomorphous series, namely the orthorhombic $R_2\overset{S}{\underset{Se}{}}O_4$ series and the monoclinic $R_2M\left(\overset{S}{\underset{Se}{}}O_4\right)_2 \cdot 6H_2O$ series, in which R may be potassium, caesium, rubidium, ammonium, or thallium, and M may be any one of a number of bivalent metals, though discussion is limited chiefly to the zinc and magnesium compounds.

The members of each series were submitted to a comparative study in regard to their external form and various vector properties, as refractive index, birefringence, and expansion coefficients. A number of these properties were shown to vary progressively when a heavier metal is substituted for a lighter, but apparently these variations do not bear any simple mathematical relation to the atomic weights. A marked divergence of the ammonium and thallium salts from the rest of the series is explained on the basis of their chemical differences from the true alkali metals. Similar progression, with a divergence in the cases of thallium and ammonium, is noted in the solubilities, but unfortunately the absolute solubility, in grams per liter, is discussed instead of the more significant molar solubility.

In the orthorhombic series the axes of the ellipsoid of thermal expansion were found to be coincident with the axes of the optic ellipsoid and in the monoclinic series one of the axes of the thermal ellipsoid coincides with the axis of symmetry, as might have been anticipated. It is unfortunate

that the elastic properties of oriented sections are not discussed, as they would doubtless form an interesting addition to the subject.

The author's studies of crossed axial dispersion are presented in an extremely interesting chapter. A plate shows the crossing of the optic axes due to change in wave-length, the series of figures for two temperatures being given. Although it is not pointed out by the author, these figures show that for these salts the change in position of the optic axes for monochromatic light, with increasing temperature, is in the same direction as the change in position due to decrease in wave-length at constant temperature.

The author's conclusions are concisely summarized in the next to the last chapter. The new term eutropic series is defined as a series "in which the small angular differences and also the physical properties of the crystals obey the law of progression according to the atomic weight of the interchangeable elements which give rise to the series and belong to the same family group of the periodic classification." Thus the thallium and ammonium salts belong to the above isomorphous series, but are excluded from the eutropic series to which the potassium, caesium, and rubidium salts belong.

Because of the close similarity between the ammonium and rubidium salts the author concludes that there is unoccupied space within the lattice-work of the crystal to allow for the eight additional atoms when the ammonium radical is substituted for rubidium. This may not be considered as proven, as it rests on the tacit assumption that the dimensions of the atoms, or their spheres of influence are the same, an assumption which seems hardly warranted, especially in view of Pope and Barlow's interesting explanations of the same phenomenon.

In the concluding chapter a comparison is drawn of the present status of crystallography with that of twenty years ago when the author began his work as a pioneer in the field of the more refined measurements of crystallographic characters. He points out that the measurements recorded are now on a plane of accuracy with atomic-weight determinations, whereas formerly gross errors entered into a large part of the work. Bare mention is made of the work of Pope and Barlow and their valence theory.

The book is well worth the attention of everyone interested in crystallography whether from the chemical or physical side, and leads one to look forward to the author's more general treatise which is to appear shortly.

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